

Default Disambiguation for Online Parsers

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Abstract

Since composed grammars are often ambiguous, grammar composition requires a mechanism for dealing with ambiguity: either ruling it out by using delimiters (which are awkward to work with), or by using disambiguation operators to filter a parse forest down to a single parse tree (where, in general, we cannot be sure that we have covered all possible parse forests). In this paper, we show that default disambiguation, which is inappropriate for batch parsing, works well for online parsing, where it can be overridden by the user if necessary. We extend language boxes – a delimiter-based algorithm atop incremental parsing – in such a way that default disambiguation can automatically insert, remove, or resize, language boxes, leading to the *automatic language boxes* algorithm. The nature of the problem means that default disambiguation cannot always match a user's intention. However, our experimental evaluation shows that automatic language boxes behave acceptably in 96.8% of tests involving compositions of real-world programming languages.

ACM Reference Format:

Lukas Diekmann and Laurence Tratt. 2019. Default Disambiguation for Online Parsers. In *Proceedings of the 12th ACM SIGPLAN International Conference on Software Language Engineering (SLE '19)*, October 20–22, 2019, Athens, Greece. ACM, New York, NY, USA, 14 pages. <https://doi.org/10.1145/3357766.3359530>

1 Introduction

Language composition – the ability to build larger languages out of multiple small languages – offers an enticing solution to problems such as the development of domain-specific languages or the migration of legacy software. Unfortunately,

writing and editing composed programs is often cumbersome. Arguably the major cause of this is due to ambiguity when parsing; language composition is underpinned by grammar composition; composing even two provably unambiguous grammars can lead to an ambiguous grammar; and determining whether a grammar is unambiguous or not is undecidable [Cantor 1962]. There are two fundamental approaches to dealing with such ambiguity: either ruling it out through the use of delimiters (via explicit bracketing or syntax-directed editing); or using a generalised parsing algorithm that can create a parse forest, capturing all ambiguities (e.g. [Visser et al. 1997]). Each has different trade-offs: delimiters are visually intrusive and/or awkward to work with; and one can never know if enough disambiguation operators have been used to filter all possible parse forests down to a single parse tree.

In this paper we show that default disambiguation – i.e. a disambiguation strategy applied equally to every language composition – provides a satisfying new point in the design space. This may seem surprising, since default disambiguation is clearly inappropriate for batch parsing, where a single incorrect disambiguation will cause dire results. The realisation underlying this paper is that this is not an issue for online parsers, since users can manually override incorrect disambiguations. However, this introduces a new challenge: default disambiguation must mostly match the users intentions, because if they have to override it too often then the system will be perceived as unusable.

In this paper we use *language boxes* as the basis of a default disambiguation system. Language boxes aim to combine the advantages of explicit bracketing and syntax-based editing [Diekmann and Tratt 2014]. Editors which support language boxes need to use incremental parsing (we assume use of the Wagner [1998] algorithm): unlike traditional editors, users do not directly edit a contiguous block of text in memory, but instead indirectly edit a parse tree, which is continuously updated as they type. A language box is then simply a node in the parse tree that represents a different language, surrounded by explicit, but invisible, delimiters. Unlike explicit bracketing approaches, there are no visually intrusive delimiters; unlike traditional syntax-based editors, the program can be syntactically incorrect in arbitrary ways and places during editing. Language boxes have the virtue that they work for any possible language composition. However, this generality comes at a cost: users must explicitly,

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SLE '19, October 20–22, 2019, Athens, Greece

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ACM ISBN 978-1-4503-6981-7/19/10...\$15.00
<https://doi.org/10.1145/3357766.3359530>

```

(a)
bool students_all_same_age() {
  Row result = SELECT min(age)
}

(b)
bool students_all_same_age() {
  Row result = SELECT min(age),
}

(c)
bool students_all_same_age() {
  Row result = SELECT min(age), max(age) FROM students|
}

(d)
bool students_all_same_age() {
  Row result = SELECT min(age), max(age) FROM students;|
}

(e)
bool students_all_same_age() {
  Row result = SELECT min(age), max(age) FROM students;
  return result.get(0) == result.get(1);
}

```

Figure 1. An example of default disambiguation in action, with elided screenshots from our implementation of the automatic language boxes algorithm within the Eco editor. Here, the user is entering text in a composition of Java and SQL, where SQL statements can be used wherever Java expressions are valid. As the user types, language boxes (with a pink background) are automatically inserted, removed, or resized. **(a)** After typing the skeleton of a Java function, the user begins typing an SQL statement as the right-hand side expression of a Java assignment. The most fundamental part of the algorithm is to try inserting language boxes when a syntax error in the outer language occurs (as can be seen at the `min` function) but not if it then leads to a syntax error immediately after the inserted language box. It is thus too early to insert an automatic language box around the SQL as it would cause a syntax error in the first non-whitespace token afterwards (`'`). **(b)** After typing `'`, an SQL language box is automatically inserted since the first non-whitespace Java token (`'`, `,`) is now syntactically valid. **(c)** The user continues typing a (now incomplete) SQL statement. This causes syntax errors in the outer language which cannot yet be resolved by inserting, removing, or resizing any language boxes. **(d)** After typing `;`, the automatic language box algorithm resizes the existing language box to encompass the entire SQL statement, making the program syntactically complete. **(e)** Further syntactically correct Java input does not cause the language box to be altered.

and tediously, state when they want to insert or remove language boxes.

We thus created default disambiguation rules which can automatically insert, remove, and resize language boxes in many useful cases — leading to the *automatic language boxes* algorithm. Given several languages in a composition, automatic language boxes find a non-strict subset of the possible ambiguous parses: in many cases, only one possibility remains, and language boxes are inserted or updated as appropriate. The algorithm is comprised of several stages / heuristics: determining what user inputs should trigger it; finding candidate language boxes to insert, remove, or resize; filtering out those which would make the overall program worse; and then applying the remaining candidates. Figure 1 shows a simple example and walks readers through the high-level parts of the algorithm and accompanying heuristics.

We implemented automatic language boxes as an extension to the Eco editor [Diekmann and Tratt 2014]. In order to validate automatic language boxes, we created 12 language compositions involving large, real-world languages (Java, Lua, PHP, and SQL), and composed programs in those compositions by extracting fragments from real-world programs. In essence, our experiment is equivalent to opening a file in the outer language, moving the cursor to a given position, deleting a fixed amount of text, and then inserting text one character at a time from the inner language. We then group the possible outcomes of such actions into two overall categories: ‘acceptable’ (roughly speaking: a language box was inserted without causing an error; or no language box was inserted because the fragment is also valid in the outer language) and ‘unacceptable’ (a language box was inserted

but caused an error elsewhere in the file; or no language box was inserted despite the fragment being invalid in the outer language). Across the 5,100 tests we ran, 96.8% are classified as acceptable, with the majority (65.8% of the total) leading to a language box being inserted around the entire fragment, and most of the rest (25.3% of the total) being instances of the fragment being valid in both the outer and inner languages. We believe that this data shows that default disambiguation is a practical means for editing composed programs. Our fully repeatable experiment can be found at <https://archive.org/details/defaultdisambiguation>.

2 Background

In this section, we briefly survey existing approaches to editing composed programs, before giving a brief overview of incremental parsing, sufficient for this paper’s purposes.

2.1 Delimiter-based Approaches

The traditional approach to language composition is to use delimiters between languages. The most obvious way of achieving this is to use explicit brackets to make clear a switch from an outer to an inner language (e.g. ‘for (String e: <<SELECT name FROM table>>) { ... }’), though this is visually intrusive (what [Bravenboer et al. 2005, p. 4] call “syntactic clutter”), and prevents the brackets being used within the sub-language (e.g. in this case, the inner language cannot use `>>` as a bit-wise operator).

Naive approaches inherit a severe restriction from traditional parsing, which separates lexing (i.e. the splitting of the user’s input into tokens) from parsing (i.e. the structuring of

tokens into a parse tree): all the languages in the composition must share the same lexing rules. This restriction can be somewhat eased if the lexer recognises the explicit brackets and extracts text between them wholesale for separate lexing and parsing (see e.g. [Tratt 2008, p. 13-14]), though it is then hard for the lexer to accurately keep track of nested brackets (e.g. should brackets in comments be counted or not? and how does one know what format comments in the inner language(s) are in?). A more sophisticated approach is for the lexer and parser to interact (see e.g. [Van Wyk and Schwerdfeger 2007]), such that the parse causes a switch in lexing rules when input shifts to an inner language. This has the advantage that brackets do not always need to be quite as visually intrusive (e.g. one can use a difference in keywords to identify a switch from one language to another), though in the general case explicit brackets must still be used to resolve ambiguities.

2.2 Scannerless Parsing

Generalised parsing can parse any Context-Free Grammar (CFG), even those that are ambiguous. Scannerless parsing [Visser et al. 1997] extends this such that lexing and parsing are specified together. This removes the need for explicit brackets entirely, but leads to more ambiguities, since traditional lexers resolve many ambiguities (e.g. between identifiers and keywords) before parsing. This is challenging because ambiguity is, in general, undecidable [Cantor 1962] and even the best ambiguity heuristics fail to find all possible sources of ambiguity [Vasudevan and Tratt 2013]. Thus, no matter how many static disambiguation operators one uses, in general one cannot be sure if all possible points of ambiguity have been covered. Furthermore, disambiguation operators can cause scannerless parsers to become context-sensitive [van Eijck 2007], the consequences of which remain unclear. Although it is possible in some cases to use semantic information such as types to aid disambiguation (see e.g. [Vinju 2005]), this is not applicable to all languages.

2.3 Syntax Directed Editing

Traditional syntax directed editing avoids parsing text entirely. In essence, users edit an AST directly, with incomplete parts of a program being represented by holes. This avoids the need for explicit delimiters, and sidesteps issues of ambiguity completely. However, such systems are awkward to use [Khwaja and Urban 1993, p. 2], for example only allowing complete subtrees in the AST to be selected at a time (e.g. for the expression `'2 + 3 * 4'` one can select `'2'` or `'3 * 4'`, but not `'2 + 3'`), and quickly fell out of fashion. The modern syntax directed editor MPS [Pech et al. 2013] alleviates some, though not all, of these problems. However, it requires significant expertise on the part of the language composition author to make editing a pleasant experience, as the AST structure places constraints on many editing operations.

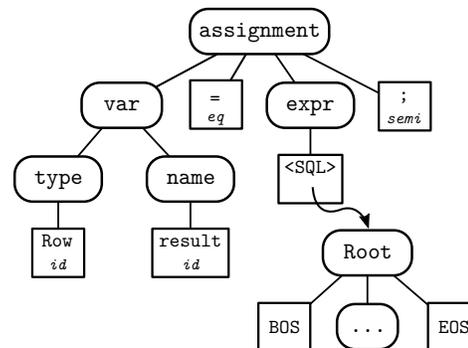


Figure 2. An elided example of a parse tree in an incremental parser with language boxes: nonterminals have a type and zero or more children; terminals have a type (top) and a value (bottom). The composition in question is, again, (outer) Java and (inner) SQL. Here, the outer Java code is an assignment (`'type name = ... ;'`). The right-hand side of the assignment is an SQL language box (the node with type `'<SQL>'`): from the perspective of the outer Java code, the SQL node is a terminal (and hence its value is irrelevant). In reality, the SQL node has a complete SQL parse tree underneath it: the special Root, BOS (Beginning Of String), and EOS (End Of String) nodes that every incremental parse tree contains, as well as the actual SQL contents (elided to `'...'` in this example).

2.4 Incremental Parsing

Parsing is traditionally a batch process: an entire file is fed through a parser and a parse tree created from it. Incremental parsing, in contrast, is an online process, continually parsing text and updating a parse tree as the user types. In this paper we make use of the incremental lexing and LR incremental parsing algorithms of Wagner [1998], taking into account the several fixes found in Diekmann [2019]. In this subsection we provide a brief overview of this algorithm sufficient to understand the rest of this paper.

The incremental lexer and parser both operate on the parse tree. Parse tree nodes are either *nonterminals* (representing rules in the grammar) or *tokens* (representing terminal symbols). Nonterminal nodes have an immutable type (e.g. `'expr'`) but a mutable list of child nodes. Tokens have a mutable type (e.g. `'int'`) and a mutable value (e.g. `'3'`) but no children.

After input from the user is received, the incremental lexer is run first. Using lookahead information, it identifies the affected area of the change, updates or creates tokens as necessary, and marks the path from each updated or created token to the root as changed. The incremental parser then runs, reparsing all subtrees with changes in them, and creating or removing nonterminals as needed.

2.5 Language Boxes

Language boxes allow users to embed one language inside another in the context of an incremental parser. From the

perspective of an outer language, a language box is a terminal. Since parsers care only about the type of a terminal, this is a natural fit. In reality, language boxes do have content, though it is not visible to the outer language: they contain a separate parse tree for the inner language within them.

This simple definition belies its power. Consider our running Java and SQL example composition. Java’s grammar must have a reference from Java’s expression rule to a special symbol type ‘language box’ (conventionally represented between angle brackets to visually separate it from rules and tokens). At run-time, if the Java parse tree has an SQL language box at the correct point, then Java considers the tree to be syntactically correct. The SQL language box will have its own SQL parse tree inside which may or may not be syntactically correct. An elided example of such a tree-of-trees can be seen in Figure 2.

Philosophically, language boxes thus form delimiters, albeit invisible ones, between languages: from a syntactic perspective, outer languages are ignorant of the contents of inner languages and vice versa. Thus we get much of the power of syntax-directed editing without the accompanying difficulty of editing ASTs. At all points, all languages can be manipulated as normal text using the incremental parsers.

3 The Outlines of a Solution

The chief weakness of language boxes is that they must be inserted manually — this involves pressing a special key combination, selecting the desired inner language from a list, typing the content, and (in general) pressing a second special key combination to complete the language box. When language boxes are used infrequently, this is merely irritating, but when language boxes are used frequently, it is a significant usability issue, impeding the user’s flow. Eco, an editor which supports language boxes [Diekmann and Tratt 2014], slightly eases this problem by using information from the incremental parser to highlight those languages valid at the point of the cursor, though this is a mild palliative at best.

In an ideal world, we would be able to automatically insert language boxes exactly, and only, when they are wanted by the user. However, this is impossible in the general case because language composition is really grammar composition in disguise, and thus subject to the same ambiguity problems as generalised parsing (see Section 2.2). We must thus lower our sights slightly, aiming to automatically insert, remove, or resize language boxes correctly merely in the vast majority of cases, with the remaining cases few enough in number that the user is willing to override them manually. This still leaves a broad solution space which we narrow down with the following soft considerations.

First, a solution which requires language composition authors (i.e. the people who actually compose grammars, create code generators etc.) to provide additional hints or commands to aid automatic language box insertion is less

likely to be used widely and/or correctly. The meta-system underlying a language composition system is often complex, and expecting language composition authors to be expert in every part of it (as well as the domain they are composing languages for!) is unrealistic. For example, it can be difficult to know whether a non-LR grammar is ambiguous or not [Vasudevan and Tratt 2013] and whether one has disambiguated it in the expected way: grammar composition magnifies such concerns, particularly as the number of languages in a composition grows.

Second, a solution which seriously degrades performance would be unacceptable. For example, one simple way of finding which language boxes to insert would be to reparse the complete file on every keypress, which would be noticeably slow for large files. Ideally, the theoretical performance guarantees of Wagner [1998] would be maintained as well as good practical performance¹.

Third, a solution which inserts language boxes unpredictably is unlikely to find favour with users. Clearly, given the hard constraint described at the start of this subsection, users cannot expect perfect language box insertion all of the time. However, a reasonable minimum expectation is that it should be entirely predictable as to when automatic language boxes are potentially inserted, removed, or resized; and, ideally, largely predictable as to what the effects of such actions are. Furthermore, false negatives (i.e. when the system inserts, removes, or resizes language boxes incorrectly) are likely to be particularly harshly received by users and must be reduced to the minimum possible.

4 Automatic Language Boxes

In this section, we present a default disambiguation mechanism in the form of the *automatic language boxes* algorithm. Given an arbitrary language composition, it uses several heuristics to find plausible places to insert, remove, or resize language boxes. The algorithm makes use of the fact that it has a surrounding parse tree to provide context, and knowledge of where the user has recently made edits, to improve the quality of its results.

To ease the algorithm’s description, we start by considering the problem of language box insertion, before then adding additional functionality (e.g. removal and resizing). We later validate the usefulness of automatic language boxes in Section 6.

4.1 The Consideration Heuristic

The first challenge with automatic language boxes is to decide upon a sensible heuristic for considering if/when to

¹Interestingly, the original implementation of this incremental parsing algorithm had to be triggered by the user (e.g. when a file was saved). Modern machines are fast enough that even a naive implementation can run comfortably on every keypress in nearly all reasonable cases.

```

1: public Row get_students() {
2:     return SELECT name FROM students;
3: }

```

Figure 3. An example of a syntax error in a Java and SQL composition. In this example, we have turned off automatic language box insertion to emphasise the fact that syntax errors often occur in the middle of the language box we would like to insert.

insert a language box – what we call the *consideration heuristic*. If the consideration heuristic triggers too frequently, it will lead to too many unwanted language boxes being inserted, each of which must then be manually removed by the user. Conversely, if it triggers infrequently, it will not be a useful aid to the user.

We use two related observations as the guides to our consideration heuristic. First, by definition, language composition always consists of an outer language and one or more inner languages². It is thus a reasonable expectation that most text typed in the outer language is intended to be in the outer language. Second, the clearest indication that recently typed text in the outer language might have been intended for an inner language is that it leads to a syntax error in the outer language.

Our consideration heuristic therefore triggers at the point of each new syntax error. This is an entirely predictable heuristic from a user perspective, though it does have two consequences: the point of a syntax error is not always at the beginning or end of the text that a user expects to be put in a language box (see Figure 3); and this heuristic clearly works better for languages whose syntaxes don't overlap a great deal (see Section 4.6). Happily, we can rely on the fact that the incremental parser isolates syntax errors after they occur [Wagner 1998, p. 93], so that there is no possibility of old syntax errors being considered a second time.

4.2 The Candidates Heuristic

Once the consideration heuristic has triggered, we then have to search for plausible nodes in the parse tree at which language boxes could be inserted – what we call the *candidates heuristic*. The trade-off here is that identifying too many locations slows down the search and overwhelms the user with possibilities; but identifying too few locations means that useful candidates are missed. We thus define several sub-heuristics which we then combine together. A candidates heuristic can produce zero or more candidate language boxes at any given point; those candidate language boxes may cover different spans and/or be of different language types. Before we define the candidates heuristics themselves,

²Note that these terms are relative: when we create a language box and move into it, the previously inner language now becomes the outer language.

```

1 def cnds_recogniser(node, lang):
2     lexer = lexer for lang starting at node
3     parser = parser for lang
4     cnds = []
5     while True:
6         token = lexer.next_token()
7         if token is None:
8             return cnds
9         parser.parse_token(token)
10        if parser.accepted():
11            cnds.append((node, token.end_pos, lang))
12        elif parser.error_node.type_ != "EOS":
13            return cnds

```

Figure 4. A generic candidates recogniser which produces the ending offsets of each substring starting at node that is valid in language lang. In essence, we create a lexer and parser for lang (lines 2–3) and then try recognising substrings that grow one token at a time (lines 6 and 9), though note that the recogniser parser reuses the previous state. If we reach the end of the parse tree we are complete (lines 7–8). If we successfully parse a substring, we add a candidate to the list (lines 10–11). If a substring causes a parse error on anything but the implicit EOS (End Of String) token, we know that growing the substring further cannot fix the parse and terminate the search (lines 12–13).

we first introduce the concept of recognisers, which all candidates heuristics use.

4.2.1 Recognisers

When a candidates heuristic has identified a node n in the parse tree as the plausible start of a language box, we then have to decide if one or more language boxes could start at that point. Although it would be possible to use the normal incremental parser to answer this question, it would require significant setting up and tearing down which would be tedious to program and slow to run. Instead we provide *candidates recognisers*³ which are able to quickly return the list of substrings valid in a language L starting at node n .

The main challenge for candidates recognisers is to decide when to stop trying to recognise further input. If we stop too early, we will fail to recognise valid language boxes, but if we go too far, we will degrade performance. The technique we use is to try recognising gradually growing substrings as valid in an inner language, making use of the fact that the recogniser parser implicitly reuses state from the previous token. If a substring is not valid, we then check where the parse failed: if it failed on the EOS (End Of String) token, then it is possible that extending the substring might lead to a valid parse, so we continue the search; but if it failed earlier than the EOS token, then we know that extending

³Some languages (e.g. whitespace sensitive languages such as Python) need slightly customised candidates recognisers.

```

1 def parse_tree(parser, node):
2     cnds = []
3     v = global_version - 1
4     while node is not None:
5         for lang in composition:
6             if lang can be shifted before node.version(v):
7                 cnds.extend(cnds_recogniser(node, lang))
8                 node = node.parent(v)
9     return cnds
10
11 def stack(parser, node):
12     cnds = []
13     for state, node in reversed(parser.stack):
14         for lang in composition:
15             if lang can be shifted at state:
16                 t = node.next_terminal()
17                 cnds.extend(cnds_recogniser(t, lang))
18     return cnds
19
19 def line(parser, node):
20     cnds = []
21     while node.type_ not in ["BOS", "Newline"]:
22         for lang in composition:
23             if lang can be shifted before node:
24                 cnds.extend(cnds_recogniser(node, lang))
25                 node = node.prev_terminal()
26     return cnds

```

Figure 5. Simplified versions of our three candidates heuristics. Each is passed a node, which is the point at which an error is detected, and finds sensible points before that node in the parse tree to be the possible starting point of language boxes (using the candidates recogniser from Figure 4). The `parse_tree` candidates heuristic walks up the parse tree to find candidate language boxes (line 6–7). Because the parse tree is, in a sense, only partially parsed at the point the candidates heuristic is called, we have to view the parse tree as it was before parsing began (line 8). The `stack` candidates heuristic walks the parse stack, finding the node matching each point in the stack (line 13) and then searches for candidate language boxes (line 15) starting at the first terminal following that node (line 16). The `line` candidates heuristic searches backwards each token from the error node (line 25) until the beginning of the line which contains that node (line 21) for candidate language boxes (line 23).

the substring cannot fix the parse and we stop the search. Figure 4 shows a more formal version of this algorithm.

For example, consider the fragment `int x = SELECT 1 + 2;` in our running Java and SQL composition. If we start a candidates recogniser at the `'SELECT'` token, we first try recognising `'SELECT'` which leads to a syntax error at the EOS token, so we continue. We then try recognising `'SELECT 1'`, which is valid SQL, so we add it to our candidates list and continue. `'SELECT 1 + '` errors at the EOS token, so we continue. `'SELECT 1 + 2'` succeeds, so we add it to our candidates list. `'SELECT 1 + 2;` errors at the `','` token, so the search then terminates, even if there is input after the fragment.

4.2.2 The Parse Tree, Stack, and Line Heuristics

We eventually created three distinct candidates heuristics, each of which has different strengths and weaknesses. We now describe each candidates heuristic in detail; see Figure 5 for a semi-formal version of each.

The *parse tree* candidates heuristic aims to find plausible candidates based on the structure of the parse tree. The intuition underlying this is that a likely point to insert a language box is around text that forms a subtree and that we can find such points by recursively walking the parent nodes of the node in which a syntax error was found. However, there is a slight subtlety in that the parse tree is, by definition, broken at the point the candidates heuristic is called. In a sense, the incremental parser parses the tree in two stages, and the

candidates heuristic is called after the first of these, when it is possible for newly inserted terminals to be detached from the tree [Wagner 1998, p. 58, 60]. Fortunately, we can solve this easily by using the versioning feature described in Wagner [1998, p. 15] which allows us to view the tree as if the first stage of parsing had not yet occurred.

The *stack* candidates heuristic is based on the idea that each point in the parsing stack naturally defines a plausible breaking point between one language and another. It walks backwards over the parsing stack, at each point looking at the associated node. This heuristic has two significant advantages: the parsing stack is nearly always small, so few additional places in the program need to be checked; and if a language box can be inserted, parsing can continue as normal from that position in the parsing stack.

The weakness of the parse tree and stack heuristics is that both try relatively few locations, and that they rely on the structure of the underlying LR grammars, which does not always match human expectations of a language's structure. The *line* candidates heuristic is therefore very different, and captures the intuition that many language boxes are intra-line: it searches backwards for candidates, one node at a time, from the error node to the beginning of the line that contains the error. This heuristic ensures that all candidate locations close to the error node are searched, but bounds the search in a way that is unlikely to cause a noticeable slowdown.

In order for later stages in the algorithm to work correctly, each candidate needs to have a valid parsing stack. While

```

1 def recreate_parsing_stack(lbox):
2     v = global_version - 1
3     path_to_lbox = set()
4     parent = lbox.parent(v)
5     while True:
6         path_to_lbox.add(parent)
7         parent = parent.parent(v)
8         if parent is None:
9             break
10
11    parser = initialise_parser
12    node = root_node
13    while node is not lbox:
14        if node in path_to_lbox:
15            node = node.children(v)[0]
16        else:
17            parser.parse(node)
18            node = node.next_lookahead()

```

Figure 6. An algorithm for efficiently creating a parse stack after a language box has been inserted into the parse tree. We do this in two steps. First we collect all the nodes on the path from the language box to the root node (lines 2–9). Second we then follow equivalent steps as when a node is marked as changed and the incremental parser runs [Wagner 1998, p. 63]: we reparse all nodes up to the language box (lines 11–18), skipping subtrees which can’t be relevant to the parsing stack (lines 17–18). The `next_lookahead` function (line 18) returns the next node in the parse tree in preorder. Note that we have to iterate over a previous version of the parse tree: `node.parent(V)` and `node.children(V)` both work in the same way e.g. `node.parent(V)` returns node’s parent as when node was in version V (which may be different to node’s parent in the current version of the tree, `global_version`).

candidates produced by the stack heuristic naturally do so, we need to create a valid parsing stack for candidates from the parse tree and line heuristics. Fortunately, we can do this efficiently by using a similar approach to that used by the incremental parser to reparse nodes (see Figure 6).

4.3 Combining Heuristics

As we shall see in Section 6, each of our candidates heuristics has strengths and weaknesses. We therefore combine them into a single candidates heuristic, imaginatively called *all*. This aggregates the candidates from the individual heuristics, filters out those which immediately break the surrounding context, ranks the remainder, and filters out all of the non-best candidates.

We first filter out language boxes which are not valid in their immediate context. By definition, our candidates heuristics will not have suggested candidate boxes which are syntactically incorrect relative to the preceding context, but they do not check the following context. A simple solution here might seem to be to filter out language boxes which are

followed by errors, but this would lead to us filtering out candidates when the user has deliberately left a later part of the program in a syntactically incomplete state. We thus filter out only those candidates where the first non-whitespace token following the candidate language box contains an error. The reason we specify the first non-whitespace token, rather than simply the first token, is that grammars for incremental parsing almost always define whitespace as a token. This means that the incremental parser often inserts a whitespace token after a candidate language box, and that whitespace token is by definition syntactically valid, though not particularly insightful. We thus need to skip such tokens in order to get to a token which tells us something useful about the context surrounding a candidate language box.

We then rank candidates by how far we can parse successfully after them without encountering a syntax error. However, since different language boxes can encompass different parts of the input, and since inserting different language boxes can change how much input subsequent tokens consume, finding a simple definition of “how far” is surprisingly difficult. Our high-level solution is to continue parsing after each candidate language box and use the absolute character offset of the first subsequent parsing error as a reasonable proxy for “how far”. In order to bound this check, we first take all the candidates and non-deterministically select one of those whose end character offset is the equal largest: we then parse 10 further tokens beyond that language box’s end to find the ‘maximal parse point’. For each remaining candidate language box, we then try parsing beyond it. If we hit a parsing error before the maximal parse point, we discard the candidate language box; if we parse up to, or beyond, the maximal parse point, we consider the candidate language box equally good to the initial candidate language box. Note that the ‘or beyond’ clause is needed because different candidate language boxes may lead to the remaining input being lexed in different ways, which may lead to tokens of different lengths being created.

4.4 Applying or Presenting Candidates

Once the ‘all’ candidates heuristic has run, we will have zero or more possible language boxes to insert. If there are zero candidates, then the algorithm completes. If there is one candidate, we simply insert it to the user’s program. If the user is unhappy with the insertion, they can remove it by pressing undo (conventionally `Ctrl` + `Z`). However, implemented naively, the language box can simply reappear on each subsequent keypress, which is unlikely to be desired. Therefore removing a language box in this way marks a flag `noinsert` on the error node identified by the consideration heuristic. The consideration heuristic ignores nodes where this flag is set to true so that language boxes are not reinserted at a point where the user has explicitly indicated they do not want them.

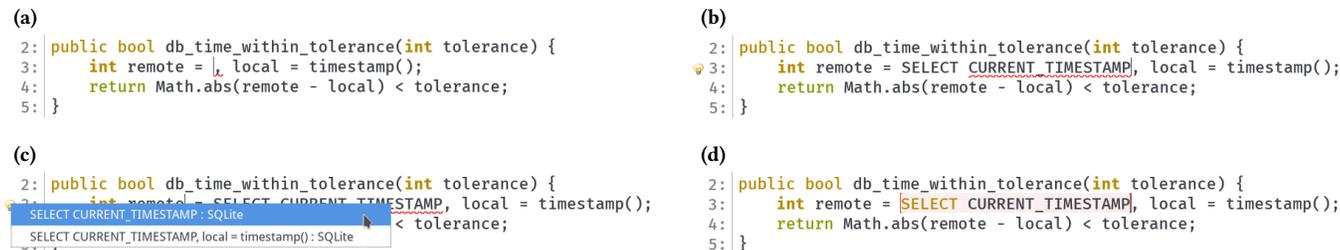


Figure 7. An example of multiple language box candidates in our running Java and SQL composition. **(a)** The user is editing an existing Java programme, and has just deleted the expression after ‘remote’. **(b)** Inserting an SQL statement leads to a syntax error in Java. The automatic language box algorithm then finds multiple valid language box candidates. Rather than picking one at random, the syntax error remains, and the existence of multiple candidates is indicated to the user by the light bulb icon next to line 3. **(c)** Clicking on the light bulb displays the candidate language boxes that could be inserted. In this example, the user clicks on the first in the drop-down list. **(d)** The appropriate language box is inserted.

However, if there are multiple candidates, we then have two choices: we could insert one of the candidates and present the others to the user as choices; or simply present all the candidates as choices without inserting any of them. The former approach is surprisingly hard to do well. If we were to non-deterministically select one candidate and insert it, the user would be unable to predict what was about to happen on each key press. We could instead rank candidates (perhaps by ‘relevance’, or length, or starting position etc.), but we were unable to find a ranking system which matches the user’s intentions often enough to be worthwhile. We therefore simply present all the candidates as options to the user from which they must choose one (see Figure 7). As we shall see in Section 6, this happens rarely enough that it is not a significant problem. It is also worth noting that this is an example of a fundamental difference between batch and online parsing: it is entirely feasible for us to ask the user for their help in choosing language boxes as that choice can be made once and recorded permanently, rather than having to be made anew on each (batch) parse.

4.5 Removing and Resizing

Automatically inserted language boxes start life in the *uncommitted* state, which means that they can then be considered possible candidates for automatic removing and resizing. Language boxes move to the *committed* state when the user shows that they have finished editing at the current point by moving the cursor outside of the language box. Users can manually change a committed box to uncommitted if they later want it to be subject to the algorithm again. If the content of an uncommitted language box, or its surrounding area, changes then it may be automatically removed or resized by the algorithm.

4.5.1 Removing

The simplest example of when we might want an automatic language box to be removed is if the user deletes a character

immediately after an automatic language box has been inserted. For example, if an SQL language box is inserted as soon as the user types ‘int x = SELECT * FROM t’ and the user then presses backspace, the automatic language box should disappear because ‘SELECT * FROM’ is valid Java and we want to prioritise the outer language in a composition (see Figure 8). The full set of situations that we handle is as follows:

1. If an uncommitted language box has a syntax error within it, and if its contents are valid in the outer language, then the language box is removed.
2. If an uncommitted language box becomes part of a syntax error in the outer language, and if its contents are valid in the outer language, then the language box is removed.
3. If an uncommitted language box’s content is valid in both the inner and outer languages, then the language box is removed if that would not then cause subsequent parse errors. Following the precedent from Section 4.3, we use the first non-whitespace token after the language box as a proxy for this.

Note, that while the first two situations are triggered by an error occurring either inside the box or on the box itself, the third situation has no clear trigger. On each run of the incremental parser we thus check the third situation for each uncommitted language box in the program. Fortunately, unless the user has manually marked some language boxes as uncommitted, the only uncommitted language boxes can be in the location of the cursor, so their number is typically small and the performance implications trivial.

4.5.2 Resizing

Although we do not change the starting position of an uncommitted language box (which can be highly distracting), its end position can be automatically changed to encompass more or less content (Figure 1 shows an example of the former). A language box is expanded to encompass more

(a) `return select * from t;` (b) `return select * from * |t;`

Figure 8. A (slightly contrived) example showing automatic language box removal in our Java and SQL composition. (a) The user meant to write a Java expression, but forgot the second ‘*’ after ‘from’: thus an SQL language box was inserted. (b) The user moves the cursor to before ‘from’ and inserts the missing ‘*’. This makes the contents of the SQL language box syntactically invalid. Since its contents are, however, valid in the outer language (Java), the language box is removed.

content if: its parse tree does not contain a syntax error; if encompassing the additional content does not cause a syntax error within the language box; and if removing the content from the outer language does not cause syntax errors in the first non-whitespace token in the outer language. Language boxes are shrunk to encompass less content if they contain a syntax error and moving the content to the outer language both fixes the error inside the language box and does not introduce additional syntax errors in the outer language.

Both growing and shrinking can be handled with our existing candidates recogniser (see Section 4.2.1). While there is a clear indicator for when a language box may need to be shrunk (e.g. when it contains an error), this is not the case for expansion. We must therefore run our altered candidates recogniser at the start of each uncommitted language box; fortunately, as in automatic language box removal (see Section 4.5.1), there are almost never enough of these to cause performance concerns. The candidates recogniser returns all the possible right hand extents of the language box. We then filter out candidates which do not meet the above conditions. If none remain, the algorithm completes; if one remains, we resize the language box appropriately; if more than one remains, we present the multiple options to the user in the same way as in Section 4.4.

4.6 Highly Ambiguous Compositions

Some language compositions are so fundamentally ambiguous that normal automatic language boxes do not work well. For example, consider a composition of Java (or any other programming language!) with HTML, where HTML language boxes can be used wherever Java expressions are valid. Since HTML’s lexer can match almost any text, nearly all syntax errors in Java can be resolved by wrapping text in an HTML language box, which is unlikely to match the user’s intentions.

To help with such cases, we thus have to relax the ‘no hints’ constraint from Section 3, allowing language composition authors to specify either the valid or the invalid token types which can appear at the start of a language box. For example, in the case of the Java and HTML composition, a good choice is to specify HTML tags as being the only valid starting token types for a candidate language box. Any such hints given by language composition authors are checked in the candidates recogniser so that inappropriate candidates do not cause pointless work in later stages of the algorithm.

5 Limitations

Since automatic language boxes are a default disambiguation mechanism, there are inevitably situations where they do not perform as well as hoped. Despite (as we shall see in Section 6) such cases being rare, it is useful to enumerate some of their fundamental weaknesses.

Although our solution to highly ambiguous compositions (see Section 4.6) works well when the outer language matches specific input (e.g. Java) and the inner language matches nearly anything (e.g. HTML), the reverse situation does not work well. For example, if we compose HTML and Java where Java expressions are valid wherever HTML tags are valid, automatic language boxes almost never trigger, since there are few ways of making a syntax error in HTML. The only way this can be solved is by using a consideration heuristic which is not triggered by syntax errors, but it is not clear to us what a good heuristic along these lines might look like.

Lexical ambiguities between languages can also cause subtle problems. For example, imagine that we compose Java and Lua, such that Lua expressions are valid wherever Java expressions are valid and then input ‘`int x = 3 // 4 + 1;`’. This leads to a syntax error at the beginning of the line following this statement and no automatic language boxes are inserted. However, this is confusing for users, since ‘//’ is Lua’s integer division operator, and they might reasonably expect a Lua language box to be put around ‘`3 // 4`’ and/or ‘`3 // 4 + 1`’. However, since ‘//’ is the Java comment prefix, ‘// 4 + 1;’ is ignored entirely, and the almost inevitable resulting syntax error is postponed to the following line or later: in such cases, not even the line candidates heuristic can find a starting point for language boxes that matches a human’s intuition. Although this example could be solved by searching a fixed number of lines backwards, only an unbounded backwards search, with its obvious performance problems, can solve the general case. Fortunately, such ambiguities are sufficiently rare that maintaining the simplicity of the line candidates heuristic seems a reasonable choice.

Automatic language boxes inherit incremental parsing’s weaknesses on multiline comments and strings. For example, in a naive Java grammar, typing ‘/*’ without the matching ‘*/’ causes the entire rest of the file (whether it is inside or outside a language box) to be relexed and tokens flattened. Interestingly, a slight variant on language boxes solves this problem for incremental parsing [Diekmann 2019, p. 108–122]. However, this is not applicable to our situation, where candidates recognisers may end up lexing until the end of

the file. Fortunately, this is unlikely to be a performance problem in practice. First, this can only happen if an inner language has sufficient lexical overlap with the outer language (e.g. sharing the same syntax for comments) and the rest of a file matches both language’s lexing rules. Second, lexing is a fast activity in general and particularly fast in the recogniser because we are not mutating the parse tree.

6 Evaluation

To evaluate the efficacy of automatic language boxes, a large-scale experiment is necessary. We first present our methodology before looking at the results of our experiment.

6.1 Methodology

Since there is no equivalent work that we know of, we have to define our own methodology.

First, in order to produce numbers that are plausibly representative of situations that real users might encounter, we created 12 language compositions of real-world languages, and created 5,100 tests from real-world programs. Each test is a tuple (*base file*, *base file function definition or expression offset*, *base file function definition or expression span*, *function definition or expression fragment*) where ‘base file’ is an instance of the outer language in the composition and ‘fragment’ is an instance of the inner language. For each test, we then loaded *base file* into our extension of Eco; emulated key presses which move the cursor to the *offset* and deleted *span* characters; and then emulated key presses which inserted *fragment*. For each test we recorded whether a language box was inserted or not, the number of characters covered by any such language box, and the cause of any errors (e.g. an insertion led to subsequent errors; or no candidates were found at all).

Second, we need to classify the outcome of each test. The overall question we want an answer to is: do automatic language boxes work well in most cases? Answering this is not completely trivial, because there are several possible outcomes from inserting text in an inner language. We break these down into six categories:

Complete insertion A language box was automatically inserted around all of the fragment.

Partial insertion (no errors) A language box was automatically inserted around part of the fragment, and the resulting text that was left in the outer language did not cause any errors.

Partial insertion (errors) A language box was automatically inserted around part of the fragment, but the resulting text that was left in the outer language caused one or more syntax errors later in the file.

No insertion (valid) No language box was automatically inserted because the fragment was valid in the outer language.

No insertion (errors) No language box was automatically inserted even though the fragment was not valid in the outer language.

No insertion (multi) No language box was automatically inserted because there were multiple candidates.

We then group these under ‘acceptable’ – complete insertion, partial insertion (no errors), no insertion (valid), and no insertion (multi) – and ‘unacceptable’ – partial insertion (errors), no insertion (errors). If automatic language boxes are to be useful, we would need to see a high value for the acceptable group and a low value for the unacceptable group.

6.1.1 Language Compositions

To create our 12 language compositions, we used the grammars of 4 real-world languages (Java 5, Lua 5.3, PHP 5.6, and SQLite 3.27). For each language composition of L_1 (outer) and L_2 (inner), we allow expressions and function definitions in L_2 to be used wherever expressions and function definitions in L_1 are normally valid. For example, in the composition JavaLua, Java is the outer language and Lua the inner language: Lua function definitions and expressions can be used wherever Java function definitions and expressions (respectively) are valid. The one exception to this is when SQL is the inner language: since our corpus consists of SQL statements, it makes little sense to allow SQL statements where a Java/Lua/PHP function is valid. In this case, we restrict the composition to only insert SQL statements where Java/Lua/PHP expressions are valid (i.e. we do not insert function definitions at all). The particular language compositions we created can be seen as the x -axis labels in Table 1.

6.1.2 Program Corpus

We then collected a corpus of inputs in each language. For PHP, we used the source code of Wordpress 4.6.13, which consists of 365 files that are valid when parsed with our PHP grammar, which total 174,147 LoC after we have stripped out the embedded HTML (which is not part of the PHP language as such). For Java, we used the Java Standard Library 5 which consists of 6,556 files and 1,888,190 LoC. For Lua, we used Lua’s test suite, which consists of 32 files totalling 13,990 LoC. For SQL, we used SQLite’s test suite, consisting of 1,042 test files which contain 27,525 tests totalling 95,533 LoC.

We then ran each file in the corpus through a parser to identify the offsets and spans of function definitions and expressions, collecting the longest match when an expression contained several subexpressions. For PHP and Java we found that most expressions are so simple (e.g. a function call with numeric parameters) that they make highly repetitive, and uninformative, tests: in these languages, we thus extracted only expressions which form the right hand side of assignments, since we found that these more often contain somewhat interesting expressions. The situation in our Lua corpus was almost reversed, with many of the syntactically

	<i>JavaLua</i>	<i>JavaPHP</i>	<i>JavaSQL</i>	<i>LuaJava</i>	<i>LuaPHP</i>	<i>LuaSQL</i>	<i>PHPJava</i>	<i>PHPLua</i>	<i>PHPSQL</i>	<i>SQLJava</i>	<i>SQLLua</i>	<i>SQLPHP</i>	<i>Overall</i>
# Tests	888	864	573	275	255	130	562	529	355	233	212	224	5,100
All	98.8%	93.4%	99.3%	98.9%	94.9%	95.4%	99.3%	97.7%	97.5%	97.9%	97.6%	85.3%	96.8%
Parse tree	76.4%	91.1%	100.0%	98.5%	93.3%	93.8%	99.5%	68.6%	98.3%	97.9%	96.2%	83.9%	89.4%
Stack	96.6%	93.8%	99.3%	97.5%	92.9%	67.7%	99.5%	97.9%	97.5%	97.0%	97.6%	85.3%	95.6%
Line	96.4%	79.9%	99.0%	98.9%	94.9%	95.4%	99.3%	95.5%	97.5%	97.9%	97.6%	85.3%	93.8%

Table 1. The total percentage of acceptable outcomes for each benchmark and heuristic. Acceptable outcomes are that: an automatic language box (covering all or part of the fragment) was inserted, causing no syntax errors; no language box was inserted since the fragment was also valid in the outer language; or there were multiple candidates which were presented to the user. Unacceptable outcomes are those which lead to syntax errors.

interesting expressions occurring in assert statements. We thus extracted all expressions from Lua files. Overall, we identified 2,474 expressions and 518 functions for PHP, 52,687 expressions and 6,743 functions for Java, 4,476 expressions and 230 functions for Lua, and 61,065 statements for SQL.

6.2 Results

We break the results of our experiment down in two ways: by acceptable results per language composition (Table 1); and by detailed outcome in the overall benchmark suite (Table 2). In both cases we show the differences in the various candidates heuristics, which shows that while each has strengths and weaknesses, collectively they work well. Appendix A contains several tables that give a more detailed breakdown of information that is, in a sense, a combination of that between Tables 1 and 2.

The results of Table 1 are clear: 96.8% of tests have an acceptable outcome with the ‘all’ candidates heuristic. Table 2 allows us to explore the sub-categories. 65.8% of tests insert a complete language box around the fragment (by definition making the program syntactically correct) and 25.3% of tests have fragments which are valid in the inner and outer language. If we exclude tests whose fragments are valid in the inner and outer language (i.e. cases where the disambiguation mechanism cannot expect to do anything useful), then 88.1% of the remaining cases insert a language box around the whole fragment – in other words, automatic language boxes match one reasonable (if slightly naive) expectation in the vast majority of cases. The remainder of cases are mostly acceptable outcomes: partial language box insertions without errors (i.e. part of the fragment is put in a language box but the remainder remains in the outer language) and no insertions due to multiple candidates are both roughly equal in proportion.

That leaves the two unacceptable cases. ‘Partial insertions (errors)’ (2.3% of tests) are cases where a language box was inserted around part of the fragment, but some was left in the outer language, causing a syntax error later in the file.

One solution to this might seem to be to increase our search of the parse tree for errors after a language box has been inserted, but this would come at a cost since we cannot reliably distinguish syntax errors caused by language box insertion from syntax errors caused by incomplete or deliberately incorrect user input. A better solution might be to experiment with comparing the number and location of syntax errors before and after candidate language box insertion, though this can only lessen, not fully solve, the problem. ‘No insertions (errors)’ (0.8% of tests) means that a language box was not inserted around the fragment because it seemed to be valid in the outer language even though it caused a syntax error later in the program. Solving this problem suffers from the same problem as for partial insertions with errors, and, since it is such a small proportion, is not a significant issue.

Both Tables 1 and 2 present the statistics for our individual candidates heuristics. One might assume that the lines candidates heuristic is the most effective, because it correctly deals with nearly all insertions of expression fragments. However, its weakness is the JavaPHP composition with only 79.9% tests having an acceptable outcome. This is largely because the initial line of a PHP function (e.g. ‘function x() {’) looks like a Java function (with a return type ‘function’): it is thus parsed as a Java function which leads to syntax errors on subsequent lines of PHP code.

We expected the parse tree candidates heuristic to be more effective than the stack candidates heuristic, but the latter (95.6%) has a noticeably greater proportion of acceptable outcomes than the former (89.4%). A generic weakness of the parse tree heuristic is that many languages have grammar rules along the lines of ‘if (expr) { ... }’ i.e. we expect a language box to be inserted in the middle of the grammar rule. This defeats the parse tree heuristic entirely, though the stack heuristic works as per human intuition. The stack candidates heuristic, however, performs poorly on LuaSQL because of the nature of Lua’s grammar. For example, in the mixed Lua/SQL program ‘x = SELECT a, b FROM t’, everything up to ‘b’ can be parsed in Lua, leading to an LR

	Complete insertion (No errors)	Partial insertion (No errors)	Partial insertion (Errors)	No insertion (Valid)	No insertion (Errors)	No insertion (Multi)
All	65.8%	2.8%	2.3%	25.3%	0.8%	2.9%
Parse tree	58.5%	3.1%	1.0%	25.3%	9.6%	2.5%
Stack	64.9%	2.9%	2.0%	25.3%	2.4%	2.5%
Line	63.3%	2.8%	2.3%	25.3%	3.8%	2.5%

Table 2. The total percentage of outcomes by category. See page for a detailed description of each category. The largest categories by far are ‘complete insertion (no errors)’, which means that a language box was inserted around the entire input and ‘no insertion (valid)’ which means that no language box was inserted because the fragment was valid in the outer language. Significantly, the unacceptable categories (‘partial insertion (error)’ and ‘no insertion (error)’) constitute a very small portion of the total.

reduction action which removes ‘SELECT’ from the parsing stack, making it impossible for the heuristic to identify that as a valid location to insert a language box at.

6.3 Threats to Validity

There are two overall threats to validity to our evaluation.

First, it is possible that our suite of language compositions and corpus of programs are unrepresentative. We have reduced these chances somewhat by using 4 real-world programming languages and a fairly large number of well-known programs written in those languages, but it is possible to compose very different styles of languages, and to compose them in very different ways. Doing so might change our view of the automatic language boxes algorithm.

Second, we have made various suggestions about performance needs in this paper, but Eco is a poor vehicle for evaluating whether automatic language boxes match such claims: it is written in Python and the GUI runs only in CPython, a particularly slow implementation; and Eco’s data-structures were originally designed to aid experimentation, and not performance. For example, nodes in Eco’s parse tree are very heavy weight (with a base size of around 2KiB per node, which grows rapidly as undo history is added), and do not include any of the optimisations described in Wagner [1998] (which would reduce the base node size to approximately a tenth of its current size and substantially reduce the costs of additional undo history). Despite that, editing performance with automatic language boxes is rarely noticeable. To try and get some idea of what the overhead might be with a more efficient implementation, we altered Eco so that it can be run without the GUI on PyPy, a faster implementation of Python. On a Xeon CPU E3-1270 3.60GHz machine, we then recorded the time each fragment took to be inserted. The average per-keypress wall-clock time (including everything associated with automatic language boxes) was 0.004s. Out of 5,100 tests, 7 (0.14%) had an average per-keypress wall-clock time above 0.1s (often considered the threshold at which humans start to perceive some lag from typing),

with a worst case of 0.30s. These results are fairly good as-is, although we believe that a more efficient implementation could reduce these timings by at least an order of magnitude.

7 Conclusions

In this paper we showed that default disambiguation within an incremental parser works well for language composition, providing a new point in the editing design space.

Acknowledgments

This research was funded by the EPSRC Fellowship *Lecture* (EP/L02344X/1).

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A Tables

In this appendix, we show detailed outcomes by candidates heuristic, in similar fashion to Table 2.

	Complete insertion (No errors)	Partial insertion (No errors)	Partial insertion (Errors)	No insertion (Valid)	No insertion (Errors)	No insertion (Multi)
JavaLua	56.4%	2.4%	1.1%	34.6%	0.1%	5.4%
JavaPHP	86.3%	4.7%	4.4%	1.5%	2.2%	0.8%
JavaSQL	94.4%	0.2%	0.7%	4.7%	0.0%	0.0%
LuaJava	51.3%	4.4%	0.4%	41.8%	0.7%	1.5%
LuaPHP	84.3%	6.7%	1.2%	0.8%	3.9%	3.1%
LuaSQL	86.2%	0.8%	1.5%	8.5%	3.1%	0.0%
PHPJava	42.0%	4.8%	0.5%	49.6%	0.2%	2.8%
PHPLua	47.8%	3.2%	1.7%	42.0%	0.4%	4.7%
PHPSQL	93.5%	0.0%	2.3%	3.9%	0.3%	0.0%
SQLJava	32.2%	0.9%	1.3%	60.9%	0.9%	3.9%
SQLLua	32.1%	1.9%	2.4%	50.0%	0.0%	13.7%
SQLPHP	60.3%	0.4%	14.7%	23.2%	0.0%	1.3%

Table 3. The *all* candidates heuristics

	Complete insertion (No errors)	Partial insertion (No errors)	Partial insertion (Errors)	No insertion (Valid)	No insertion (Errors)	No insertion (Multi)
JavaLua	36.8%	0.0%	0.2%	34.6%	23.3%	5.0%
JavaPHP	83.2%	6.4%	0.5%	1.5%	8.4%	0.0%
JavaSQL	95.3%	0.0%	0.0%	4.7%	0.0%	0.0%
LuaJava	52.7%	3.6%	0.4%	41.8%	1.1%	0.4%
LuaPHP	82.7%	6.7%	0.8%	0.8%	5.9%	3.1%
LuaSQL	84.6%	0.8%	1.5%	8.5%	4.6%	0.0%
PHPJava	37.4%	10.7%	0.2%	49.8%	0.4%	1.6%
PHPLua	19.7%	2.3%	0.2%	42.2%	31.2%	4.5%
PHPSQL	94.4%	0.0%	1.4%	3.9%	0.3%	0.0%
SQLJava	32.2%	0.4%	0.4%	60.9%	1.7%	4.3%
SQLLua	32.5%	0.5%	1.9%	50.0%	1.9%	13.2%
SQLPHP	58.5%	0.0%	12.5%	23.2%	3.6%	2.2%

Table 4. The *parse tree* candidates heuristics

	Complete insertion (No errors)	Partial insertion (No errors)	Partial insertion (Errors)	No insertion (Valid)	No insertion (Errors)	No insertion (Multi)
JavaLua	54.5%	2.4%	0.5%	34.6%	2.8%	5.2%
JavaPHP	87.3%	4.9%	4.1%	1.5%	2.2%	0.1%
JavaSQL	94.4%	0.2%	0.7%	4.7%	0.0%	0.0%
LuaJava	49.8%	5.1%	0.4%	41.8%	2.2%	0.7%
LuaPHP	82.4%	6.7%	1.2%	0.8%	5.9%	3.1%
LuaSQL	58.5%	0.8%	0.8%	8.5%	31.5%	0.0%
PHPJava	43.4%	5.2%	0.4%	49.8%	0.2%	1.1%
PHPLua	48.0%	3.4%	0.2%	42.2%	1.7%	4.3%
PHPSQL	93.5%	0.0%	2.3%	3.9%	0.3%	0.0%
SQLJava	31.3%	0.9%	1.7%	60.9%	1.3%	3.9%
SQLLua	32.5%	1.9%	2.4%	50.0%	0.0%	13.2%
SQLPHP	59.8%	0.4%	14.7%	23.2%	0.0%	1.8%

Table 5. The *stack* candidates heuristics

	Complete insertion (No errors)	Partial insertion (No errors)	Partial insertion (Errors)	No insertion (Valid)	No insertion (Errors)	No insertion (Multi)
JavaLua	54.6%	2.4%	1.1%	34.6%	2.5%	4.8%
JavaPHP	74.0%	4.2%	4.3%	1.5%	15.9%	0.2%
JavaSQL	94.1%	0.2%	0.7%	4.7%	0.3%	0.0%
LuaJava	51.3%	4.4%	0.4%	41.8%	0.7%	1.5%
LuaPHP	84.3%	6.7%	1.2%	0.8%	3.9%	3.1%
LuaSQL	86.2%	0.8%	1.5%	8.5%	3.1%	0.0%
PHPJava	43.4%	5.2%	0.5%	49.6%	0.2%	1.1%
PHPLua	45.6%	3.2%	1.7%	42.0%	2.6%	4.7%
PHPSQL	93.5%	0.0%	2.3%	3.9%	0.3%	0.0%
SQLJava	32.2%	0.9%	1.3%	60.9%	0.9%	3.9%
SQLLua	32.1%	1.9%	2.4%	50.0%	0.0%	13.7%
SQLPHP	60.3%	0.4%	14.7%	23.2%	0.0%	1.3%

Table 6. The *line* candidates heuristics