

An Improved Algorithm for Redundancy Detection Using Global Value Numbering

Nabizath Saleena* and Vineeth Paleri*

Abstract

Global value numbering (GVN) is a method for detecting equivalent expressions in programs. Most of the GVN algorithms concentrate on detecting equalities among variables and hence, are limited in their ability to identify value-based redundancies. In this paper, we suggest improvements by which the efficient GVN algorithm by Gulwani and Necula (2007) can be made to detect expression equivalences that are required for identifying value based redundancies. The basic idea for doing so is to use an anticipability-based `Join` algorithm to compute more precise equivalence information at join points. We provide a proof of correctness of the improved algorithm and show that its running time is a polynomial in the number of expressions in the program.

Keywords

Equivalent Expression, Global Value Numbering, Herbrand Equivalence, Strong Equivalence Dag

1. Introduction

Global value numbering (GVN) is a popular method for detecting equivalence among program expressions. A GVN algorithm is considered to be complete (or precise), if it can detect all of the Herbrand equivalences from amongst the program expressions. Two expressions are said to be Herbrand equivalent (or transparent equivalent) if they are computed by the same operator that has been applied to equivalent operands [1-3].

Even though GVN has many applications, as mentioned in [1], its main application is for code optimization in compilers, especially in detecting value based redundancies. The idea of using GVN for identifying value-based redundancies was conceived by Kildall [4]. In fact, Kildall formulated this with the aim of detecting common subexpressions in programs. An optimization using this algorithm will also subsume local value numbering [5, 6]. Kildall's GVN algorithm is well known for its precision, but is not considered efficient. Most of the efficient GVN algorithms that followed Kildall concentrate on detecting equalities among variables and hence, are limited in their ability to identify value-based redundancies [3, 7]. Rosen et al. [2] is an attempt at using GVN for partial redundancy elimination (PRE) [8-10]. Briggs et al. [11] give a comparison of the different techniques for value numbering with respect to their use in different kinds of optimizations. A recent work of VanDrunen and Hosking [12] is on the

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use of GVN for PRE. Most of the GVN algorithms [3, 7, 13, 14] require the program to be represented in static single assignment (SSA) form [15].

Gulwani and Necula [1] (hereafter referred to as GVN-GN) is a recent polynomial time algorithm for GVN. Similar to Kildall [4], this algorithm is also based on abstract interpretation. GVN-GN is designed to detect Herbrand equivalences among terms that are of size at most s , where s is the program size. A data structure called Strong Equivalence DAG (SED) is used for representing the equivalence information at any program point. The SED is a directed acyclic graph (DAG) representation of expressions, in which the common substructures are shared. Associated with each kind of node in the flow graph, a transfer function is defined. Given an SED at the input point of a node, the algorithm computes the SED at the output point of the node by using the transfer function associated with the node. For a join node, GVN-GN uses a `Join` function to compute the join of the input SEDs. Given two SEDs, the `Join` function does a variable-based intersection of the input SED nodes. Hence, the algorithm is complete in detecting Herbrand equivalences among program variables. However, a variable based intersection limits the application of this algorithm in redundancy detection. We have observed that it is possible to miss some of the redundancies, including instances of the classical common subexpression elimination and local value numbering.

In fact, at a join point, by doing a pair of wise intersection of all the SED nodes, the algorithm could achieve completeness in detecting all Herbrand equivalences. But then, theoretically, a join of multiple SEDs can yield an exponential number of nodes in the resulting SED. The important observation is that for the purpose of redundancy detection, it is not necessary to keep all of the SED nodes that result from a join. The basic idea is to keep only those SED nodes that represent terms that are anticipable at the join point. With this, we limit the number of SED nodes to at most n_e , where n_e is the maximum number of expressions in the program.

Our algorithm requires a preprocessing stage, which will annotate every program point with the set of anticipable expressions at that program point. At the join points, GVN-GN computes a variable-based intersection of the SED nodes. With the additional step of computing a term-based intersection, we get the equivalence information that is required for identifying value-based redundancies. The result is an efficient GVN algorithm that can be directly used for identifying value-based redundancies. We show that the running time of the algorithm is a polynomial in the number of expressions in the program. Even though our emphasis is on detecting total redundancies, these improvements make the algorithm easily extendable to the general problem of detecting value-based partial redundancies.

We start with a simplified overview of GVN-GN in Section 2. We present some cases of missing equivalences in Section 3. This is followed by a presentation of our method of computing an anticipability-based join in Section 4. A proof of correctness and an analysis of the running time of the improved algorithm are given in Section 5. Some additional issues with GVN-GN are presented in Section 6, and in Section 7 we present our conclusions.

2. The GVN Algorithm by Gulwani and Necula [1]: An Overview

Gulwani and Necula [1] present a polynomial time algorithm for GVN. The algorithm is designed to detect Herbrand equivalences among terms that are of size at most s , where s is the program size. We will now present a brief overview of the algorithm. In our discussions, we follow the same notations as in [1].

2.1 Representation of Equivalence Information

A data structure called SED is used for representing the equivalence information at every program point. The SED is a directed acyclic graph representation of expressions. It is similar to the structured partition DAG in [16]. Each SED represents a partition of expressions and each node in the SED represents an equivalence class. A node is denoted by $\langle V, t \rangle$, where V is a set of program variables labeling the node and t is the type of the node. A node with type \perp or c (a constant) has no successors, whereas, a node with type $F(\eta_1, \eta_2)$ has two ordered successors, η_1 and η_2 . For example, Fig. 1 shows a program node containing the assignment $z := F(x, y)$, and two SEDs G_{in} and G_{out} representing the equivalence information at its input and output points, respectively. Here G_{in} consists of three nodes and it represents the partition $\{\{z\}, [x, 1], [y, 2]\}$. In G_{out} , the node $\langle z, F \rangle$ has two successors, $\langle x, 1 \rangle$ and $\langle y, 2 \rangle$. This node represents the equivalence class $[z, F(x, y), F(1, y), F(x, 2), F(1, 2)]$.

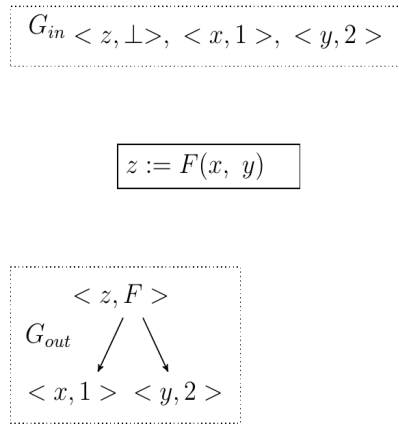


Fig. 1. SEDs representing equivalence information.

2.2 Transfer Functions

Given an SED at the input point of a node, the algorithm computes the SED at the output point of the node by using the transfer function associated with the node. Transfer functions are defined for the assignment node, the non-deterministic assignment node, and the non-deterministic conditional node [1].

2.3 Join Function

The equivalence information at the input of a join node is computed by means of a Join function. Given two SEDs, G_1 and G_2 , and an integer s' , $\text{Join}(G_1, G_2, s')$ returns an SED G such that G implies all equivalences among terms that are of size at most s' , that are implied by both G_1 and G_2 . The basic step in Join is the invocation of a recursive function $\text{Intersect}(Node_{G_1}(x), Node_{G_2}(x))$, for every variable x in the program ($Node_{G_i}(x)$ returns the node in SED G_i , with label x). For SED nodes η_1 and η_2 , $\text{Intersect}(\eta_1, \eta_2)$ returns an SED node η such that η represents all expressions that are of size at most s' and that are represented by both η_1 and η_2 .

2.3.1 Computing Join: An Example

Fig. 2 shows a program fragment with the SEDs that GVN-GN computes at program points p_1 , p_2 and p_3 . G_i is the SED at program point p_i . SED G_3 results from the join of G_1 and G_2 . The `Join` algorithm invokes `Intersect()` for each variable. `Intersect(<x, 1>, <x, 3>)` results in the node $\langle x, \perp \rangle$ in G_3 and `Intersect(<y, 2>, <y, 4>)` results in the node $\langle y, \perp \rangle$ in G_3 . The node $\langle z, F \rangle$ in G_1 represents the equivalence class $[z, F(x, y), F(1, y), F(x, 2), F(1, 2)]$. The node $\langle z, F \rangle$ in G_2 represents the equivalence class $[z, F(x, y), F(3, y), F(x, 4), F(3, 4)]$. `Intersect(<z, F>, <z, F>)` results in the node $\langle z, F \rangle$ in G_3 , which represents $[z, F(x, y)]$.

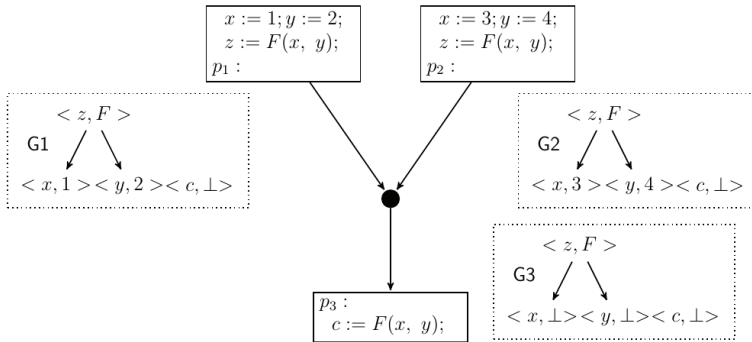


Fig. 2. Join of SEDs: G_i is the SED at program point p_i . $G_3 = \text{Join}(G_1, G_2)$.

3. GVN-GN and Detection of Value Based Redundancies

Let us now look at how we can make use of the equivalence information computed by GVN-GN in detecting value based redundancies. Consider a node n that contains an expression e . Let G_m be the SED computed by the algorithm at the entry of n . If $e \in \text{Terms}(\eta)$ for some node η in G_m , then we can conclude that whenever control reaches the entry of n , an expression equivalent to e has been already computed and hence, the occurrence of e in n is redundant. For example in Fig. 2, for the SED G_3 , $F(x, y) \in \text{Terms}(z, F)$. This indicates that when control reaches the point p_3 , in every path reaching p_3 , an expression equivalent to $F(x, y)$ is computed. Hence, it is clear that the occurrence of $F(x, y)$ in the last node is redundant.

What we have shown in Fig. 2 is an example for which the algorithm works fine. However, we have observed that there are cases for which the computed SED does not have the information required for redundancy detection, thereby limiting the use of this algorithm in related applications. In the following section, we show some examples of equivalences missed by GVN-GN.

3.1 Case of Missing Equivalences

Fig. 3 shows an example which, similar to Fig. 2, is a case where the occurrence of $F(x, y)$ in the last node is redundant. We will now show that with the equivalence information η computed by GVN-GN, it is not possible to detect this redundancy. The basic step in the Join algorithm invokes `Intersect()`

for each variable. For the variable a , $\text{Intersect}(\langle a, F \rangle, \langle a, \perp \rangle)$ results in $\langle a, \perp \rangle$ in G_3 . For the variable b , $\text{Intersect}(\langle b, \perp \rangle, \langle b, F \rangle)$ results in $\langle b, \perp \rangle$ in G_3 . The case for the variables x , y and c is also similar. In G_1 , $F(x, y) \in \text{Terms}(\langle a, F \rangle)$ and in G_2 , $F(x, y) \in \text{Terms}(\langle b, F \rangle)$. But for no node η in G_3 , $F(x, y) \in \text{Terms}(\eta)$. As such, the redundancy in this case goes undetected. To have $F(x, y)$ represented by a node in G_3 , there should be an invocation of $\text{Intersect}(\langle a, F \rangle, \langle b, F \rangle)$. However, this is never invoked from $\text{Join}(G_1, G_2)$.

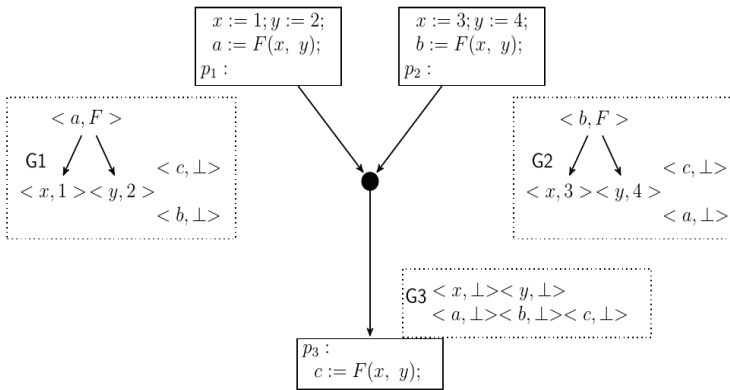


Fig. 3. Case of missing equivalences: for program point p_i , G_i is the SED that GVN-GN computes. $G_3 = \text{Join}(G_1, G_2)$. $\text{Intersect}(\langle a, F \rangle, \langle b, F \rangle)$ is not invoked.

The examples in Figs. 2 and 3 are similar except in the names of variables. The reason why Gulwani and Necula [1] fails in the second example is that there are no common variables labeling the nodes representing the expression $F(x, y)$. This will be the case with any GVN algorithm that detects variable based equalities. The example clearly shows that this is not enough for redundancy detection in general.

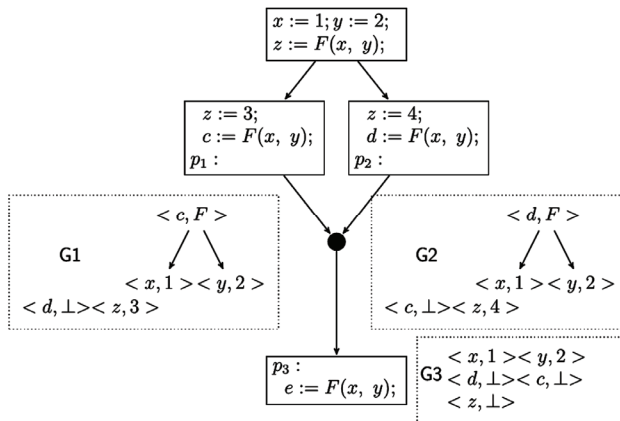


Fig. 4. Case of missing equivalences: for program point p_i , G_i is the SED that GVN-GN computes. The expression $F(x, y)$ and its equivalent expressions are not represented in the SED G_3 .

Fig. 4 shows an additional example in which all the occurrences of $F(x, y)$ are Herbrand equivalents. The node $\langle c, F \rangle$ in G_1 represents the equivalence class $[c, F(x, y), F(1, y), F(x, 2), F(1, 2)]$ and the node

$\langle d, F \rangle$ in G_2 represents the equivalence class $[d, F(x, y), F(1, y), F(x, 2), F(1, 2)]$. But there is no node in G_3 that represents the equivalence class $[F(x, y), F(1, y), F(x, 2), F(1, 2)]$. Here, whenever control reaches p_3 , an expression equivalent to $F(x, y)$ is already computed. However, there is no way to deduce this information from the SED G_3 .

4. Anticipability-Based Join

The basic problem with the `Join` algorithm in GVN-GN is that it computes intersection of only those SED nodes having at least one common variable (see line 3 of the `Join` algorithm: *for each variable* $x \in T \dots \text{Intersect}(\text{Node}_{G_1}(x), \text{Node}_{G_2}(x))$). For the example in Fig. 3, in G_1 , $F(x, y) \in \text{Terms}(\langle a, F \rangle)$ and in G_2 , $F(x, y) \in \text{Terms}(\langle b, F \rangle)$. Now, to have $F(x, y)$ represented by a node in G_3 , there should be an invocation of `Intersect` ($\langle a, F \rangle, \langle b, F \rangle$). In general, if there is an expression e such that $e \in \text{Terms}(\eta_1)$ and $e \in \text{Terms}(\eta_2)$ for some nodes η_1 of G_1 and η_2 of G_2 , then to have e represented by a node in the resulting SED there should be an invocation of `Intersect`(η_1, η_2). This suggests that to have the required information at a join point the `Join` algorithm should compute the intersection of every pair of nodes of the two SEDs that have at least one common expression. Hence, a solution that will enable the algorithm to detect these kinds of equivalences is to modify the `Join` algorithm in such a way that it computes the intersection of every pair of nodes in the two SEDs

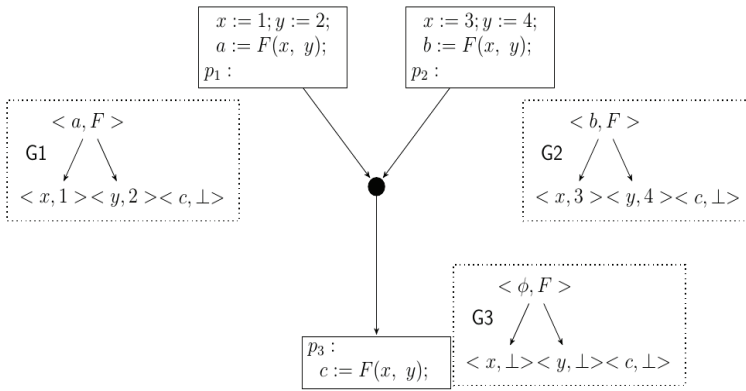


Fig. 5 Anticipability-based Join: G_3 is the SED resulting from the join of G_1 and G_2 . The expression $F(x, y)$ is represented by $\langle \phi, F \rangle$ in G_3 .

The approach of computing a pairwise intersection of the SED nodes will yield a precise algorithm. But theoretically, when we compute the join of n SEDs, it can result in an SED whose size is exponential in n . Furthermore, it can result in SED nodes representing non-program expressions. Here it is important to observe that for the purpose of redundancy detection, we do not need to keep all of the resulting nodes. The idea is to keep only those nodes η such that $e \in \text{Terms}(\eta)$ for some expression e that is anticipable at the join point. This requires a preprocessing stage to compute the set of anticipable expressions at every program point.

Fig. 5 shows the SED computed by this approach for the example in Fig. 3. The intersection of $\langle a, F \rangle$ in G_1 and $\langle b, F \rangle$ in G_2 results in the node $\langle \phi, F \rangle$ in G_3 , which represents the class $[F(x, y)]$. It should be

noted that Gulwani and Necula [1] consider nodes like $\langle \phi, F \rangle$ with an empty set of variables to be unnecessary. But in fact, these are necessary (as will be shown later) and as such, the proposed method will retain such nodes.

Fig. 6 shows the SED computed by the proposed method for the example in Fig. 4. The intersection of $\langle c, F \rangle$ in G_1 and $\langle d, F \rangle$ in G_2 results in the node $\langle \phi, F \rangle$ in G_3 , which represents the class $[F(x, y), F(x, 2), F(1, y), F(1, 2)]$. Since $F(x, y)$ is anticipable, the method retains this node.

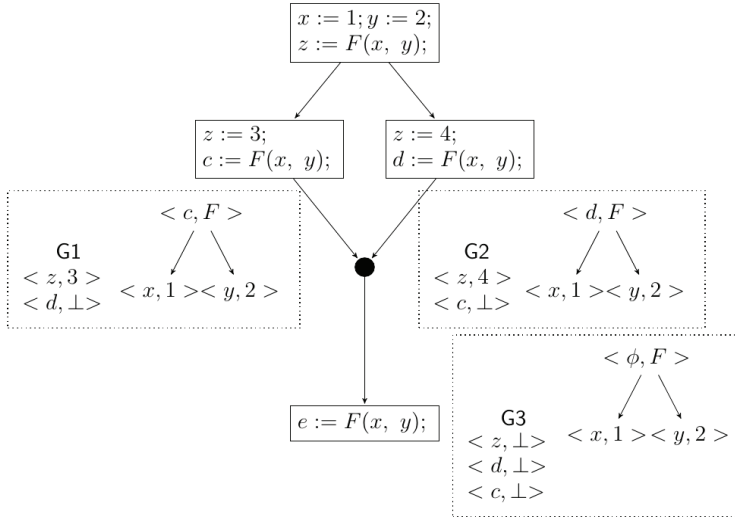


Fig. 6. Anticipability-based Join: G_3 is the SED resulting from the join of G_1 and G_2 .

4.1 Improved Algorithm

The following function `Join_Improved` shows the improved `Join` algorithm that computes the join of SEDs G_1 and G_2 . The argument s' is similar to that in `GVN-GN`. The additional argument ant_exp is the set of expressions that are anticipable at the join point. We assume that the set of anticipable expressions are precomputed at every program point using the classical anticipability analysis [9, 10]. T is the set of all program variables

```

Join-Improved ( $G_1, G_2, s', ant\_exp$ ) =
1  for all nodes  $\eta_1 \in G_1$  and  $\eta_2 \in G_2$ 
2      memoize [ $\eta_1, \eta_2$ ] := undefined;
3   $G = \phi$ ;
4  for each variable  $x \in T$  in the order  $\langle_{G_1}$  do
5      counter :=  $s'$ ;
6      Intersect ( $Node_{G_1}(x), Node_{G_2}(x)$ );
7  for each expression  $e \in ant\_exp$  do
8      counter :=  $s'$ ;
9      Intersect ( $FindNode(G_1, e), FindNode(G_2, e)$ );
10 return  $G$ ;

```

The function $FindNode(G, e)$ is similar to $GetNode(G, e)$ in GVN-GN, except that if there is no node in G representing e , then instead of extending G with a new node, the function returns $\langle \varphi, \perp \rangle$. The definition of $FindNode(G, e)$ is given below.

```

FindNode (G, e) =
1  match e with
2  y: return NodeG(y);
3  F(e1, e2):let η1 = FindNode(G, e1) and η2 = FindNode(G, e2)
4      in if (⟨V, F(η1, η2)⟩ ∈ G return (⟨V, F(η1, η2)⟩);
5      else return (⟨φ, ⊥⟩);

```

5. Correctness Proof and Analysis

In this section, we present the correctness proof and time complexity analysis of the improved algorithm.

5.1 A Note on the Correctness Proof in GVN-GN

The Soundness and Completeness proof of $Join$ (Lemma 4) in [1] relies on the property of $Intersect$, which is stated as Proposition 3 in [1]. With respect to the examples we discussed in the previous sections, we can see that there are cases where this property does not hold. We now state the property as given in [1] ($Terms(\eta_i)$ denotes the set of terms represented by the node η_i).

Proposition 3 (as given in [1]). *Let $\eta_1 = \langle V_1, t_1 \rangle$ and $\eta_2 = \langle V_2, t_2 \rangle$ be any nodes in SEDs G_1 and G_2 , respectively. Let $\eta = \langle V, t \rangle = Intersect(\eta_1, \eta_2)$. Suppose that $\eta \neq \langle \varphi, \perp \rangle$; hence, the function $Intersect(\eta_1, \eta_2)$ adds the node η to G . Let α be the value of the counter variable when $Intersect(\eta_1, \eta_2)$ is first called. Then,*

(P1) $Terms(\eta) \subseteq Terms(\eta_1) \cap Terms(\eta_2)$.

(P2) $Terms(\eta) \supseteq \{e \mid e \in Terms(\eta_1), e \in Terms(\eta_2), size(e) \leq \alpha\}$.

Now, for the example shown in Fig. 4, let $\eta_1 = \langle c, F \rangle$, in G_1 , and $\eta_2 = \langle d, F \rangle$, in G_2 . We get $Intersect(\eta_1, \eta_2) = \langle \varphi, F \rangle \neq \langle \varphi, \perp \rangle$. But we have already seen that since the nodes have no common variables, the $Join$ algorithm never invokes $Intersect(\eta_1, \eta_2)$. Hence, against what is stated in the proposition, the node $\langle \varphi, F \rangle$ is not added to G_3 . The expression $F(x, y) \in Terms(\eta_1)$ and $F(x, y) \in Terms(\eta_2)$. But for no node $\eta_i \in G_3$, $F(x, y) \in Terms(\eta_i)$. Hence, the (P2) part of Proposition 3 does not hold in this case. We can see that with the $Join$ algorithm in GVN-GN, Proposition 3 holds for the case of nodes $\eta_1 = \langle V_1, t_1 \rangle$, $\eta_2 = \langle V_2, t_2 \rangle$ such that $V_1 \cap V_2 \neq \varphi$. However, it need not hold if $V_1 \cap V_2 = \varphi$, except when $Intersect(\eta_1, \eta_2)$ is invoked recursively from another $Intersect$ call.

5.2 The Completeness Proof of $Join_Improved$

The algorithm $Join_Improved$ invokes $Intersect(\eta_1, \eta_2)$ for a pair of nodes (η_1, η_2) from the

two SEDs such that either $V \in (Terms(\eta_1) \cap Terms(\eta_2))$ for some $V \in T$ or $e \in (Terms(\eta_1) \cap Terms(\eta_2))$ for some expression e that is anticipable at the join point. This can result in nodes of the form $\langle \varphi, t \rangle$ where t is either F or c , for some constant c . Now, since $t \neq \perp$, Line 11 of `Intersect` will add the resulting node to G_3 . Therefore, we restate Proposition 3 as follows:

Proposition 3’. *Let $\eta_1 = \langle V_1, t_1 \rangle$ and $\eta_2 = \langle V_2, t_2 \rangle$ be any nodes in SEDs G_1 and G_2 , respectively such that either $V \in (Terms(\eta_1) \cap Terms(\eta_2))$ for some $V \in T$ or $e \in (Terms(\eta_1) \cap Terms(\eta_2))$ for some expression e that is anticipable at the join point. Let $\eta = \langle V, t \rangle = Intersect(\eta_1, \eta_2)$. Suppose that $\eta \neq \langle \varphi, \perp \rangle$; hence, the function `Intersect` (η_1, η_2) adds the node η to G . Let α be the value of the counter variable when `Intersect` (η_1, η_2) is first called. Then,*

(P1) $Terms(\eta) \subseteq Terms(\eta_1) \cap Terms(\eta_2)$.

(P2) $Terms(\eta) \supseteq \{e \mid e \in Terms(\eta_1), e \in Terms(\eta_2), size(e) \leq \alpha\}$.

Now, we state the following Lemma on the Soundness and Completeness of `Join_Improved` ($Terms(G_i)$ denotes the set of terms represented by the nodes of SED G_i):

Lemma 2’ (Soundness and Completeness of `Join_Improved`).

Let $G = Join_Improved(G_1, G_2, s)$. Then,

1. If $G \vdash e_1 = e_2$, then $G_1 \vdash e_1 = e_2$ and $G_2 \vdash e_1 = e_2$. If $G_1 \vdash e_1 = e_2$ and $G_2 \vdash e_1 = e_2$, such that $size(e_1) \leq s$ and $size(e_2) \leq s$ then $G \vdash e_1 = e_2$
2. For an expression e of the form $F(e_1, e_2)$, if $e \in Terms(G)$, then $e \in Terms(G_1)$ and $e \in Terms(G_2)$. If $e \in Terms(G_1)$ and $e \in Terms(G_2)$, such that $size(e) \leq s$, and e is anticipable at the join point, then $e \in Terms(G)$.

As in [1], the proof of this Lemma follows from Proposition 3’ and the definition of \vdash .

5.3 Fixed Point Computation

We have seen that the `Join_Improved` algorithm does intersections of even pairs of nodes with no common variables. We limit the number of nodes based on anticipability to at most n_e , where n_e is the number of expressions (including variables and constants) in the program. This implies that the improved algorithm needs to execute each flowchart node at most n_e times (as in [1], we assume the standard work list implementation [6]).

5.4 Correctness of the Algorithm

The Soundness Theorem and the Completeness Theorem for the improved algorithm are given below:

Theorem 2’ (Soundness Theorem). *Let G be the SED computed by the algorithm at some program point P after fixed point computation. Then,*

1. if $G \not\vdash e_1 = e_2$, then $e_1 = e_2$ holds at program point P .
2. if $e \in Terms(G)$, then either e , or an expression equivalent to e , is available at P .

As stated in [6], the Soundness proof directly follows the soundness of the assignment operation, the non-det-assignment operation, and the soundness of `Join_Improved`.

Theorem 3' (Completeness Theorem). *Let G be the SED computed by the algorithm at some program point P after fixed point computation.*

1. if $e_1 = e_2$ is an equivalence that holds at P such that $\text{size}(e_1) \leq s$ and $\text{size}(e_2) \leq s$, then $G \models e_1 = e_2$.
2. if e is an expression that is available at P such that $\text{size}(e) \leq s$ and e is anticipable at P , then $e \in \text{Terms}(G)$.

The proof is similar to that in [6], except that in order to prove the second part of the above theorem, we extended Lemma 5 of GVN-GN [1] to include the following statements: *Suppose an expression equivalent to e (with the same restrictions on $\text{size}(e)$) is available at P along every path in S , such that e is anticipable at P , then, $e \in \text{Terms}(G)$.*

5.5 Complexity Analysis

It is now clear that the improvements make the algorithm more precise. We now show that even with these improvements, the time complexity will still remain polynomial. With the additional step in `Join_Improved`, the number of nodes in an SED is at most n_e , where n_e is the number of expressions in the program. Therefore, a `Join_Improved` will invoke at most $O(n_e^2)$ `Intersect` calls. The running time of `Join_Improved` (G_1, G_2, s') will be $O(s' \times n_e^2)$, which is a polynomial in the number of expressions in the program (the use of the counter variable ensures that the depth of recursion is $O(s')$). The size of the SED resulting after a `Join_Improved` call will be at most n_e and thus, the time taken for computing the join of n SEDs will be $O(n \times s' \times n_e^2)$.

6. GVN-GN: Problems with the Removal of SED Nodes

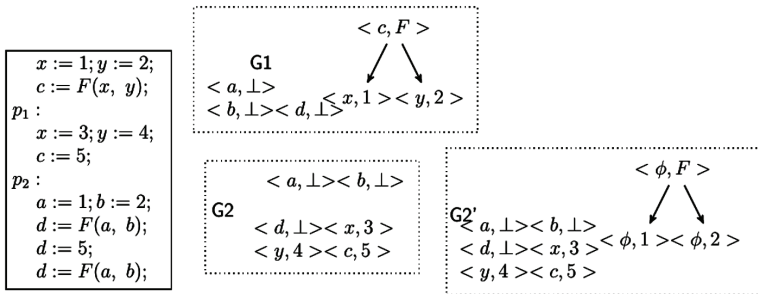


Fig. 7. Removal of “unnecessary” nodes: G_1 and G_2 are the SEDs at points p_1 and p_2 , respectively. G_2' is the SED required at p_2 .

Here we will discuss an additional problem with GVN-GN that prevents the detection of some of the equivalences that even a local value numbering algorithm will detect. Fig. 7 shows a basic block in a program with the SEDs G_1 and G_2 at program points p_1 and p_2 , respectively. The expressions $F(x, y)$ and

the two occurrences of $F(a, b)$ are equivalent and this equivalence will be detected by a local value numbering algorithm [2]. It goes undetected in Gulwani and Necula [1] because of the reasons laid out below.

In Section 3.1 of Gulwani and Necula [1], it is stated that the transfer functions may yield SEDs with unnecessary nodes, and that these unnecessary nodes may be removed (a node is considered unnecessary when all of its ancestor nodes or all of its descendant nodes have an empty set of variables). Also, it is stated in Section 5.1 that the data structure (SED) represents only those partition classes that have at least one variable. G_2' is the SED that would have been computed if there is no removal of SED nodes. Nevertheless, the algorithm considers the three nodes $\langle \varphi, 1 \rangle$, $\langle \varphi, 2 \rangle$ and $\langle \varphi, F \rangle$ as unnecessary and hence these nodes will be removed. This results in SED G_2 .

6.1 Missing Equivalences

It can be observed that the node $\langle \varphi, F \rangle$ in G_2' represents the expression $F(1, 2)$, which is equivalent to $F(x, y)$ and $F(a, b)$. With the removal of this node, we lose the information that the expressions $F(x, y)$ and $F(a, b)$ are equivalent. Similarly, since the variable d is redefined after the first assignment $d := F(a, b)$, the equivalence between the two occurrences of $F(a, b)$ goes undetected.

6.1.1 The solution

From the above example, it is clear that the problem is due to the removal of some *necessary* nodes, which the algorithm considers to be unnecessary. The simple solution is to retain all such nodes. In that case, for the above example, the SED reaching the input point of $d := F(a, b)$ will have a node representing the expression $F(a, b)$, which will indicate that an expression equivalent to it has already been computed.

7. Conclusion

The main application of GVN is for code optimization in compilers, especially in detecting value based redundancies. The examples shown in Figs. 3 and 4 for the case of missing equivalences are instances of the classical common subexpressions. The example in Fig. 7 is an instance of local value numbering. These are enough evidence to show that the improvements are necessary for the practical adaptation of this GVN algorithm [1] in code optimizations. The suggested improvements result in a more precise and polynomial time algorithm for GVN.

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