Fast Copy Coalescing and Live-Range Identification

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ABSTRACT

This paper presents a fast new algorithm for modeling and reasoning about interferences for variables in a program without constructing an interference graph. It then describes how to use this information to minimize copy insertion for ϕ-node instantiation during the conversion of the static single assignment (SSA) form into the control-flow graph (CFG), effectively yielding a new, very fast copy coalescing and live-range identification algorithm.

This paper proves some properties of the SSA form that enable construction of data structures to compute interference information for variables that are considered for folding. The asymptotic complexity of our SSA-to-CFG conversion algorithm is $O(n\alpha(n))$, where n is the number of instructions in the program.

Performing copy folding during the SSA-to-CFG conversion eliminates the need for a separate coalescing phase while simplifying the intermediate code. This may make graph-coloring register allocation more practical in just in time (JIT) and other time-critical compilers For example, Sun's Hotspot Server Compiler already employs a graph-coloring register allocator[10].

This paper also presents an improvement to the classical interference-graph based coalescing optimization that shows a decrease in memory usage of up to three orders of magnitude and a decrease of a factor of two in compilation time, while providing the exact same results.

We present experimental results that demonstrate that our algorithm is almost as precise (within one percent on average) as the improved interference-graph-based coalescing algorithm, while requiring three times less compilation time.

Categories and Subject Descriptors: D.3.4 [**Programming Languages**]: Processors — *compilers, optimization*

General Terms: Algorithms, Languages, Theory

Additional Keywords and Phrases: Register allocation, code generation, copy coalescing, interference graph, live-range identification

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1. INTRODUCTION

It has long been known that copies can be folded during the construction of the SSA form [2]. Essentially, each variable that is defined by a copy is replaced in subsequent operations by the source of that copy. The implementation of this strategy has a couple of subtle problems but is otherwise an effective optimization. In effect, copy folding during SSA construction deletes all of the copies in a program, except for those that must be used to instantiate ϕ-nodes.

This simple observation may reduce the number of copies in a program, but naive ϕ-node instantiation introduces many unnecessary copies. In our experience, the number of copies used to instantiate ϕ-nodes is much higher than the number of copies in the original code.

Classically, to solve this problem one would coalesce SSA names into a single name using an interference graph, as described by Chaitin [5, 4]. The interference graph models names as nodes, and edges between the nodes represent an interference — there is at least one point in the code where the two name are simultaneously live. The intuition for register allocation is that if two variables interfere, we will have to use a different register for each variable. The same holds true for copy coalescing: if two names joined by a copy interfere, the copy is necessary and cannot be coalesced.

Unfortunately, this conceptually simple method requires a data structure that is quadratic in the number of names. As Cooper, *et al.* showed [6], the cost of building an interference graph is significant, and for JIT compilers or other systems where compile time is crucial, this cost may be prohibitive.

This paper presents a new algorithm that performs copy coalescing without building an interference graph. We model interferences using a combination of liveness and dominance information. We present a theoretic background that shows that our optimization is safe. We present experimental data that shows that, on average, our implementation of this algorithm rivals the effectiveness of the interference-graph coalescer in removing dynamic copies while using only a fraction of the compilation time required by that algorithm.

2. SSA PROPERTIES

This section presents a brief description of the SSA properties that we use to construct our algorithm. A full formal description, along with the proofs of all the lemmas and theorems is presented elsewhere [3].

The preliminary step in our algorithm is to ensure that the code is in *regular* form, which we shall define with the following construction. We start with a standard CFG, (N, E, b_0), made up of a set of N nodes, E edges, and a unique start node, b_0. We impose an added restriction on the code in the incoming CFG, that it be *strict*.

DEFINITION 2.1. *A strict program is one in which, for every variable, v, and for every use of v, every possible path from b_0 to the use of v passes through one of the definitions of v.*

Strictness is a requirement for languages such as Java, but it can be imposed on languages like C or Fortran as well by initializing every variable at the start of b_0. The initializations that are unnecessary can then be removed by a dead-code elimination pass, or, alternatively, we can restrict the initializations to only those variables that are in the live-in set of b_0. Since the live-in set of b_0 should be empty, variables that make it into this set are those for which there is an upwards-exposed use of the variable, and thus some path from the use backwards up the CFG on which there is no definition of the variable.

Given a strict program, we then convert the code into SSA form. It is a natural result of the SSA algorithm that, after the conversion, not only is every use of a variable dominated by a single definition, but also every definition dominates all of its uses.[1] We call this a regular program.

Given a regular program, we can now define *interference*:

DEFINITION 2.2. *Two variables interfere if and only if they are simultaneously live at some point in a regular program.*

With Definition 2.2, we can prove the following theorem:

THEOREM 2.1. *If two variables in a regular program interfere, the definition point of one will dominate the definition point of the other.*

Informally, the proof for this theorem results from the fact that both variable definitions must dominate the point in the program where they interfere.

We can refine Theorem 2.1 to suit our purposes with the following theorem, which results directly from the computation of liveness:

THEOREM 2.2. *If two variables, v_1 and v_2, in a regular program interfere and the definition point of v_1 dominates the definition point of v_2, then either v_1 is in the live-in set of the block in which v_2 is defined, or both variables are defined in the same block.*

Thus, we can quickly check interference between two variables simply by examining the liveness information associated with the blocks in which the variables are defined.

3. COALESCING ALGORITHM

With the code in regular form, we can proceed with the algorithm. Essentially, we use union-find to group together all of the names joined at ϕ-nodes. We then use the previous reasoning about interference to break the union-find sets apart when we discover two members of the same set interfere. To break a set, we reinsert copies between the member that we want to remove and all of the other members of the set. At the end, all SSA names that are in the same set do not interfere, and, therefore, can share the same name. Note that we build pruned SSA [8] to make the reasoning simpler and because parts of the analysis necessary for pruned SSA, such as liveness analysis, are assumed. The algorithm we present should work for minimal or semi-pruned SSA as well, although the additional inexactness of those forms propagates itself into our analysis, possibly causing the insertion of extra copies that may not otherwise have been added.

If we had not allowed copy folding during the construction of SSA form, the initial union-find sets would contain only values that do not interfere. Indeed, this is precisely the algorithm used by a Chaitin/Briggs register allocator [5, 4, 1] to identify live ranges. The allocator joins all ϕ-node names into a single set and then builds the aforementioned interference graph. It then coalesces live ranges joined at a copy but that do not otherwise interfere. This is a classic pessimistic algorithm: all copies are assumed to be necessary until proven otherwise.

In contrast, the algorithm presented here is optimistic: we assume that *every* copy is unnecessary, and then we reinsert those that we cannot prove are unnecessary. The register allocator does not perform copy folding during SSA construction because some of those copies really are necessary — they move a value from one storage location to another, usually to free up the first location for another value. When we fold copies during SSA construction, we, in effect, transfer the information about the exchange into a ϕ-node, where we may later recover the move by inserting a new copy.

The algorithm has four steps. First, we union together all ϕ-node parameters (and the name of the ϕ-node itself). This gives us an initial guess at what are, essentially, live-range names. The second step of the algorithm compares the set members against each other, looking for interferences, which, if found, cause one of the members to be split into a new set, necessitating insertion of copies from that member to members of the first. Then a unique name is given to each set and, finally, the code is rewritten with all necessary copies.

Notice that copies are not actually inserted until the final step, for reasons described in Section 3.6. Instead, we maintain an array, $Waiting$, indexed by block name, where each entry is a list of pending copy insertions for the end of that block. When one of the earlier stages discovers a copy that needs to be inserted into some block, b, we add the copy to $Waiting[b]$. Also, because ϕ-node parameters flow along edges, we use the notation $From(x)$ to specify the block out of which the value in x flows.

3.1 Building Initial Live Ranges

The first step to coalescing copies and building live ranges is to union together the ϕ-node parameters. As we explained earlier, some of these unions will include names of variables that interfere, and one of each of these pairs will have to be removed from the set.

While we were developing the implementation of our algorithm, we found that some filtering during the building of the unions could save time and give us fewer copies. While unioning names, we detect interferences between just two names (the ϕ-node and the current parameter). Specifically, we use liveness information to detect that the SSA construction erroneously folded a copy. The folding was in error because both variables are live at some point in the code. In general, only a single copy is needed to break the interference. On the other hand, if we wait until later, each of those names may interfere with many of the other names in the union, necessitating many more copies to ensure breaking the interference. Thus, given a ϕ-node, p, defined in block b, with parameters a_1 through a_n, we apply the following simple tests of interference. These five are not exhaustive, but they handle the simple cases – any interference found will cause a copy to be inserted; otherwise, a_i is added to the union.

- If a_i is in the live-in set of b, add a copy from a_i to p in $Waiting[From(a_i)]$. Note that our liveness analysis distinguishes between values that flow into b's ϕ-nodes and values that flow directly to some other use in b or b's successors. Only in the latter case will a_i be in b's live-in set.
- If p is in the live-out set of a_i's defining block, add a copy to $Waiting[From(a_i)]$.
- If a_i is defined by a ϕ-node and p is in the live-in set of the block defining a_i, add a copy to $Waiting[From(a_i)]$.

[1] The seeming exception to this is a ϕ-node parameter, v, whose definition is in a block, b_v, not necessarily dominating the block, b_{phi}, in which v is used as a parameter. However, the "movement" of the value from the variable to the ϕ-node actually takes place along the incoming edge to b_{phi}, and this edge *is* dominated by b_v.

```
inputs:   IN   (dominator tree DT)
               (set of variables S)
outputs:  OUT  (dominance forest DF)
  for depth-first order over dominator tree nodes b
    preorder(b) = the next preorder name
    maxpreorder(b) = the largest preorder number
                     of b's descendants
  Take S in dominator order
  maxpreorder(VirtualRoot) = MAX
  CurrentParent = VirtualRoot
  stack.Push(VirtualRoot)
  for all the variables v in S in sorted order
    while preorder(v) > maxpreorder(CurentParent)
      stack.Pop()
      CurrentParent = stack.Top()
    make v a child of the CurrentParent
    stack.Push(v)
    CurrentParent = v
  Remove VirtualRoot from DF
```

Figure 1: Constructing the dominance-forest

- If a_i has already been added to another set of names because of another ϕ-node in the current block, add a copy to $Waiting[From(a_i)]$.
- If a_i and a_j are defined in the same block, then add a copy to either $Waiting[From(a_i)]$ or $Waiting[From(a_j)]$.

3.2 The Dominance Forest

At the end of the first step, we have disjoint sets of names that *may* share the same name. We now need to discover members of the set that interfere with other members of the same set.

A critical part of our algorithm is the engineering required to perform the second step efficiently. It would be prohibitively expensive to do a pairwise comparison of all the members in the set. Instead, we have developed a new data structure, called a *dominance forest*, which allows us to perform a linear comparison of set members by ordering them according to dominance information.

DEFINITION 3.1. *Let S be a set of SSA variables in a regular SSA program such that no two variables in S are defined in the same block. Let $>$ be a strict dominance relation. Let v_i be a variable in S, and B_i the block in which v_i is defined. $Dominance forest$ $DF(S)$ is a graph in which the nodes are the blocks B_i such that $v_i \in S$, and there is an edge from B_i to B_j if and only if $B_i > B_j$, and $\nexists (v_k \in S), v_i \neq v_k \neq v_j$, such that $B_i > B_k > B_j$.*

Succinctly, the dominance forest is a mapping of SSA variables to the basic blocks that contain their definition points, with the edges representing collapsed dominator-tree paths. We use Lemma 3.1 to show that we need only check edges in the dominance forest for interferences. We will show in the next section how to use the dominance forest.

Figure 1 shows the pseudo code for dominance-forest construction. This algorithm starts by adding a $VirtualRoot$ to the result to simplify the construction process. (We remove the $VirtualRoot$ at the end, which may create a forest.) In a depth-first traversal of the dominator tree, we label all nodes in the tree with their preorder sequence of traversal. On the way up in the traversal, we also compute the maximum preorder number of the descendants for each node. This number allows the algorithm to identify the antecedent-descendent information from the dominator tree in constant time and is due to Tarjan[11]. This preorder-numbering process is done only once for the whole SSA.

The algorithm iterates over the variables in order of increasing preorder number, or pn. Within the loop, a variable named $CurrentParent$ is maintained, which holds the reference to the root of the subtree currently in construction. There is an edge between $CurrentParent$ and the current variable v if $pn(v)$ is less than or equal to the the largest preorder number of $CurrentParent$, which means that $CurrentParent$ dominates v. Traversing the variables in increasing order of $pn(v)$ ensures that no edges are inserted prematurely (if a dominates b, which dominates c, the relationship will be: $pn(a) < pn(b) < pn(c)$, which will ensure that only the edges (a, b) and (b, c) are inserted and not the edge (a, c)).

3.3 Walk the Forests

We built the dominance forests to reduce the number of interferences for which we have to check. We can do this using the following Lemma:

LEMMA 3.1. *Given variable v_i defined in block b_i and variable v_j defined in block b_j, if b_j is a child of b_i in the dominance forest and v_i does not interfere with v_j, then v_i cannot interfere with any of the variables represented by b_j's descendants in the dominance forest.*

Informally, the proof of this Lemma comes from the fact that if v_i interferes with any of the v_j's descendents — for example v_k, then v_i must interfere with v_j, since it must be live at the definition point of v_k, thus it must be live at the definition of v_j.

Lemma 3.1, in essence, prunes the pairwise search space of names in a set. That is, it shows that when we map the names of some set onto its dominance forest, each variable, v, needs to be compared only to those variables defined in blocks immediately descendant of the block defining v.

Figure 2 contains the algorithm for finding and resolving interferences within a dominance forest. The dominance forest is traversed depth first. If a variable, v, interferes with any other variable in the dominance forest, v must interfere with one of its children. Because variables are checked for interference only against their children in the dominance forest, any parent variable that interferes with its child forces us to insert all of the copies necessary to break any interferences between the two. This has the effect of separating the variable from any of its more distant descendants it might interfere with.

3.4 Local Interferences

Up to this point, only liveness information at block boundaries has been considered. However, there are situations where two variables do not interfere at any block boundaries but are nonetheless live in the same block. This happens when one of the variables, v_1, is live coming into the block where the second variable, v_2, is defined. In this case, we need to ensure that v_1's last use occurs before v_2 is defined, which requires a walk through the block to determine. Our algorithm keeps a list of variable pairs that need to be checked for local interference. After traversing all of the dominance forests and before inserting actual copies, our algorithm traverses each block backwards to find and break any of these local interferences.

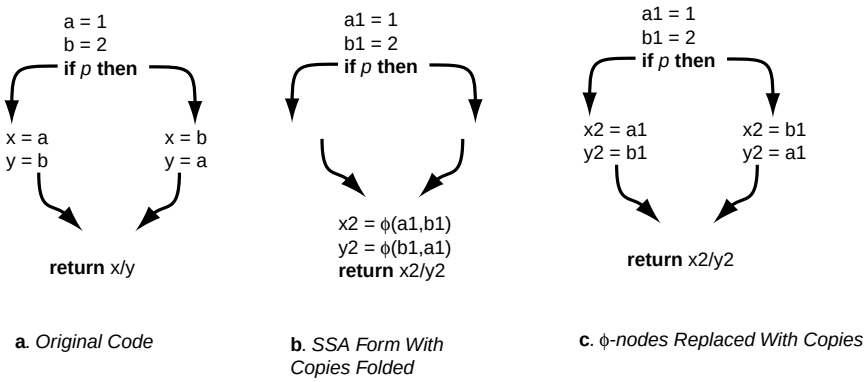
3.5 Renaming Variables

Once copies have been inserted, those variables that are still connected by ϕ-nodes need to be given a single unique name. Naive iteration over ϕ-nodes and renaming the parameters to a single name is not sufficient. If a variable were a parameter to multiple ϕ-nodes, the variable would be renamed multiple times, resulting in incorrect code.

The solution is to iterate over all those variables that are candidates for renaming (those that were a part of one of the union-find sets and are not on the list of variables to remove from the

for depth-first traversal of DF_i
  if variable p is c's parent and is in the $live - out$ set of c's defining block
    if p can not interfere with any of its other children and c has fewer copies to insert than p
      Insert copies for c and make c's children p's children
    else insert copies for p
  else if parent p is in the $live - in$ set of c's defining block or p and c have the same defining block
      Add the variable pair (p, c) to the list to check for local interference later

Figure 2: Finding and resolving interferences

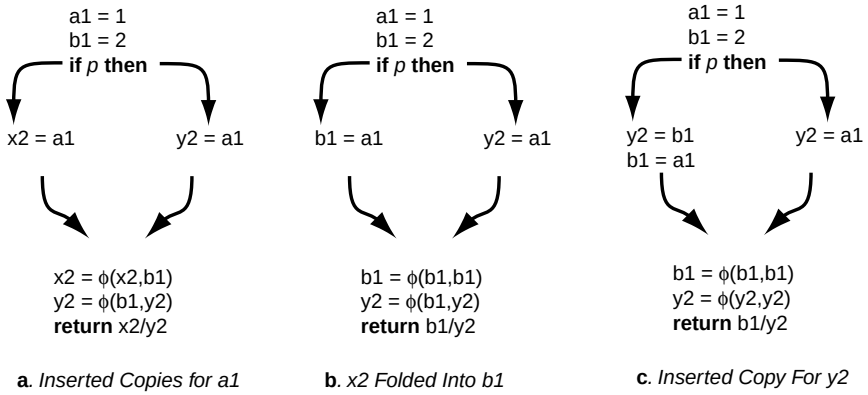


a. *Original Code*

b. *SSA Form With Copies Folded*

c. *ϕ-nodes Replaced With Copies*

Figure 3: The "virtual swap" problem



a. *Inserted Copies for a1*

b. *x2 Folded Into b1*

c. *Inserted Copy For y2*

Figure 4: Inserting copies for the "virtual swap" problem

set by inserting copies) and rename them to a single unique name. The $Find$ function will return a single unique name per set, and that name can be used for renaming all members of that set.

3.6 Correct Copy Insertion

We have to be careful when inserting copies for ϕ-nodes, because naive copy insertion may produce incorrect code. Two such problems, the "lost copy" problem, and the "swap" problem, are described in detail by Briggs, *et al.* [2]. We avoid the "lost copy" problem by splitting critical edges after we have read in the code. The "swap" problem is addressed as in Briggs, *et al.* by careful ordering of copies with temporaries inserted to break any cycles. This is precisely the reason that we use the $Waiting$ array to store pending copies; as Briggs, *et al.* show, the ordering of the full set of copies to be inserted is critical to correctness.

The "virtual swap" problem is a case similar to the "swap" problem, but has to be addressed with special attention when attempting to produce the minimal number of copies. In the "virtual swap" problem, two variables are defined by copies on either side of a conditional, and they take opposite values on opposing sides.

3.6.1 The "Virtual Swap" Problem

Figure 4 illustrates an example where the naive insertion of copies still produces *correct* code. However, a careful implementation is needed when the copies are inserted into the SSA in our algorithm. The naive algorithm inserts all copies for the ϕ-nodes, while our algorithm attempts to insert as few copies as possible. When analyzing the ϕ-nodes, the algorithm determines that the variables $a1$ and $b1$ are simultaneously live at the end of the first block and cannot be folded together. The algorithm then picks one of them and inserts copies for it. On the left of the Figure 4 we show the example from Figure 3 with $a1$ being picked for copy insertion.

After the copies have been inserted, the last pass of the algorithm scans through the SSA and renames the variables as needed. This is the point where some additional interferences can be identified and some additional copies needed. In Figure 4b, all appearances of $x2$ have been replaced with $b1$. This exposes an interference between the first and the second ϕ-nodes, which forces insertion of a copy on Figure 4 c.

3.7 Algorithmic Complexity

The dominance-forest construction algorithm is linear in the size of the join set. It starts with a depth-first traversal of the dominator tree, which is linear in size of the dominator tree, but it is done only once for the whole SSA. It then uses the radix sort [7] to sort the variables in the set, which is linear as well since the number of variables in the join set cannot be greater than the number of basic blocks in the CFG. Each of the variables in the set is visited exactly once in the loop. So the complexity of the dominance forest construction algorithm is $O(|S|)$.

The copy insertion algorithm begins with constructing join sets for variables in the ϕ-nodes of the graph. This can be done in $O(n\alpha(n))$ time using the union-find algorithm [7], where n is the number of variables in ϕ-nodes, and α is the inverse Ackermann's function. The algorithm then constructs the dominance forests for these sets (which are disjoint), which is linear in the total number of variables in ϕ-nodes. For each dominance forest, the algorithm visits all the edges, which is linear in the number of nodes in the forest. At the end, all ϕ-nodes are visited and the variables that are the arguments of the ϕ-nodes are renamed into a single variable name. The total complexity of this algorithm is $O(n\alpha(n))$, where n is the total number of arguments in all the ϕ-nodes in the SSA.

Since the inverse of Ackermann's function is practically a constant, one cannot hope to achieve better algorithmic complexity than what is presented here, since all the ϕ-nodes and all of their arguments *have* to be visited at least once in the SSA-to-CFG conversion.

4. EXPERIMENTS

In this section, we present experimental evidence to show that this algorithm is both effective and efficient. We compare our algorithm against two versions of the interference-graph coalescer. One is simply a coalescing phase stripped from our implementation of a Chaitin/Briggs register allocator. The second is an improved version, made possible by an insight into building the interference graph, that is significantly faster than the original, but equally precise.

The test suite we used in our experiments is made up of 169 routines that come from Forsythe, *et al.*'s book on numerical methods[9], as well as the Spec and Spec '95 libraries. We ran these codes on a minimally loaded 300 MHz Sparc Ultra 10 with 256 megabytes of memory. Due to space constraints, we only report on the ten largest results in each experiment. We took the ten programs that took longest to compile using the standard SSA-to-CFG conversion for Table 2 and Table 3 and the ten programs with the most dynamic copies for Table 4 and Table 5. However, we think that these give a reasonable insight into the behavior of the algorithms. We use the following nomenclature to distinguish the algorithms:

- *Briggs* – the Chaitin/Briggs interference-graph coalescer
- *Briggs** – the improved interference-graph coalescer, below
- *Standard* – the Briggs, *et al.* ϕ-node-instantiation algorithm that does not attempt to eliminate any copies
- *New* – the algorithm presented herein.

4.1 Engineering the Interference-Graph Coalescer

During the development of the experiments to test this new algorithm, we discovered a simple oversight in building the interference graph as described by Briggs in his dissertation. Briggs' algorithm requires four steps. First, the code is converted to SSA form. Names are then joined to form live ranges by unioning ϕ-node parameters. The third step is a loop in which the interference graph is built and then copies whose source and destination do not interfere have those live ranges coalesced. Because the interference graph is not exact, it needs to be rebuilt after all of the coalescible copies have been identified and those live ranges have been unioned together. This can expose additional opportunities for coalescing, so these two steps are iterated until all opportunities have been found. For these experiments, the final step is to rewrite the code to reflect the namespace described by the live ranges.

This algorithm is simple and powerful, but it is very expensive. The interference graph is modeled as a triangular bit matrix, with as many rows or columns as there are live-range names. This data structure requires $n^2/2$ bits that have to be cleared. As Cooper, *et al.* showed [6], this is a considerable part of the overall running time of a graph-coloring register allocator.

The flaw in this algorithm is that it builds an interference graph that includes the full set of live-range names. The reason for this is that if the coalescing phase does not fold any copies, the interference graph is correct, and the remaining phases of the allocator then use it. However, if the coalescing phase unions any live ranges,

File	Algorithm		$\frac{Briggs*}{Briggs}$	Memory Usage (in bytes)			
				First Pass		Second Pass	
	Briggs	Briggs*		Briggs	Briggs*	Briggs	Briggs*
fieldX	3.10	1.55	0.53	2120664	83521	1553762	1139
parmvrX	2.53	1.26	0.53	1968409	8281	1800293	380
parmovX	2.26	1.11	0.51	1701720	7140	1556880	324
twldrv	2.20	0.49	0.23	598689	24806	426735	715
fpppp	1.28	0.03	0.02	950137	0		
radfgX	1.25	0.73	0.58	446224	90300	215296	4900
radbgX	1.22	0.67	0.56	405132	80940	200928	5005
parmveX	0.95	0.46	0.51	453939	4556	395012	182
jacld	0.57	0.15	0.26	82225	8695	50512	0
smoothX	0.46	0.25	0.52	175561	23562	104976	1640
AVERAGE	1.58	0.67	0.42				

Table 1: Time (in seconds) and memory (in bytes) comparison for the interference-graph coalescers

the interference graph has to be rebuilt, and in our experiments, we rarely saw input that did not require at least two iterations (and few that required more). While the build/coalesce loop, as Briggs calls it, is iterating, the interference graph should only be built using live-range names that are involved in copies. To maintain a compact namespace, this requires an extra mapping array, but the cost of accessing the array each time a name is examined is offset by the considerable decrease in the size of the interference-graph bit matrix. Table 1 shows the difference in memory used to build the interference graph. Clearly, the savings in memory usage is immense, and the time required to perform coalescing is, on average, less than half the time with our improved algorithm.

To our knowledge, this is the first publication of this insight. Certainly, comparison of our SSA-coalescing algorithm has to be made against the best known coalescer (which, in this case, is the Briggs' algorithm improved by using the insights described above), which these experiments do.

4.2 Running Time

Table 2 shows the running time of the three algorithms, the original SSA ϕ-node replacement algorithm presented in Briggs, *et al.*, the algorithm presented in this paper, and the improved coalescer from our register allocator. The timer was started immediately before building SSA form, and its value is recorded immediately after the code is rewritten in its various forms by the different algorithms.

Clearly, the additional analysis to restrict the number of copies is more expensive than the universal copy-insertion algorithm. However, our algorithm is considerably faster than the interference-graph coalescer.

Table 3 shows the maximum amount of memory used by the three algorithms during compilation. Over the full test suite, our algorithm uses, on average, 40% more memory than the standard ϕ-node-replacement algorithm. It uses only 21% more memory than the improved interference-graph coalescer, which itself uses substantially less memory than the previous state of the art. This table and Table 2 show that memory usage alone is not the only determinant of the compiler's total running time.

4.3 Efficacy Measurements

In Table 4, we show the number of copy operations that were executed. Our algorithm produces code that executes about 1% fewer copies, on average, than the interference-graph coalescer. The interference-graph coalescer tries to remove copies out of innermost loops first, on the theory that these are the most profitable to remove. This heuristic sometimes fails, as in the case of $initX$, but it also sometimes wins; on some of the codes in the test suite, our algorithm results in code that executes up to two-thirds again as many copy operations as the code produced by the interference-graph coalescer.

In Table 5, we show a static measurement of copies left in the code by the three algorithms. On average, our algorithm leaves in approximately three percent more static copies than the interference-graph coalescer, but as with dynamic copies, the results vary significantly. Again, we believe this reflects the heuristic nature of both algorithms.

5. CONCLUSIONS AND FUTURE WORK

In this paper, we give a theoretical background that enables fast computation of interference information and present a practical, efficient algorithm to perform copy folding without building an interference graph. The applications of this algorithm are many. It can be used as a standalone pass of an optimizer. It can replace the current copy-insertion phase of an optimizer's SSA implementation. Finally, it can replace the coalescing phase of a Chaitin/Briggs register allocator.

Our experiments show that this algorithm provides significant improvements in running time over an interference-graph-based algorithm, while maintaining comparable precision. These results make this algorithm very attractive for use in any system, including, perhaps, systems in which compile time is a critical concern, such as JIT compilers.

We have also presented an implementation insight concerning building an interference graph for copy coalescing that can be trivially inserted into existing graph-coloring register allocators to make them run much faster.

Our plan for future research includes design and implementation of a fast register-allocation algorithm that uses the results presented in this paper. We will also consider implementation of several heuristics to improve the precision of this algorithm without sacrificing the compilation time.

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File	Standard	New	Briggs*	$\frac{New}{Standard}$	$\frac{New}{Briggs*}$
parmvrX	0.17	0.38	1.26	2.24	0.30
fieldX	0.17	0.48	1.55	2.82	0.31
parmovX	0.15	0.30	1.11	2.00	0.27
radfgX	0.10	0.24	0.73	2.40	0.33
radbgX	0.10	0.22	0.67	2.20	0.33
twldrv	0.07	0.16	0.49	2.29	0.33
parmveX	0.06	0.13	0.46	2.17	0.28
initX	0.06	0.11	0.26	1.83	0.42
advbndX	0.04	0.07	0.15	1.75	0.47
deseco	0.03	0.07	0.20	2.33	0.35
AVERAGE	0.10	0.22	0.69	2.20	0.32

Table 2: Comparison of compilation times (in seconds)

File	Standard	New	Briggs*	$\frac{New}{Standard}$	$\frac{New}{Briggs*}$
parmvrX	4214880	5365964	5126100	1.27	1.05
fieldX	3144244	5062808	3513180	1.61	1.44
parmovX	3740196	4785972	4562856	1.28	1.05
radfgX	1594768	2379156	1785964	1.49	1.33
radbgX	1492484	2250356	1695244	1.51	1.33
twldrv	1496208	1805984	1613080	1.21	1.12
parmveX	1734400	2204940	2081044	1.27	1.06
initX	1456780	1814224	1680640	1.25	1.08
advbndX	1009844	1253616	1130072	1.24	1.11
deseco	614496	954356	718856	1.55	1.33
AVERAGE	2049830	2787738	2390704	1.36	1.17

Table 3: Comparison of compiler memory usage (in bytes)

File	Standard	New	Briggs*	$\frac{New}{Standard}$	$\frac{New}{Briggs*}$
tomcatv	23572565	64571	64571	0.00	1.00
blts	17222000	3716100	3666100	0.22	1.01
buts	17111000	4055500	4050500	0.24	1.00
getbX	8197640	63520	63520	0.01	1.00
twldrv	5244414	215761	217777	0.04	0.99
smoothX	4213120	599920	467440	0.14	1.28
rhs	3509310	414324	414324	0.12	1.00
parmvrX	2218540	43610	42630	0.02	1.02
saxpy	2000000	20000	20000	0.01	1.00
initX	1755598	92810	390455	0.05	0.24

Table 4: Comparison of dynamic copies executed

File	Standard	New	Briggs*	$\frac{New}{Standard}$	$\frac{New}{Briggs*}$
tomcatv	112	47	47	0.42	1.00
blts	82	36	31	0.44	1.16
buts	72	33	31	0.46	1.06
getbX	176	28	28	0.16	1.00
twldrv	976	164	169	0.17	0.97
smoothX	668	283	215	0.42	1.32
rhs	678	32	27	0.05	1.19
parmvrX	352	101	101	0.29	1.00
saxpy	4	1	1	0.25	1.00
initX	458	106	118	0.23	0.90

Table 5: Comparison of static number of copies

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