Iterated Register Coalescing

LAL GEORGE
Lucent Technologies, Bell Labs Innovations
and
ANDREW W. APPEL
Princeton University

An important function of any register allocator is to target registers so as to eliminate copy instructions. Graph-coloring register allocation is an elegant approach to this problem. If the source and destination of a move instruction do not interfere, then their nodes can be coalesced in the interference graph. Chaitin's coalescing heuristic could make a graph uncolorable (i.e., introduce spills); Briggs et al. demonstrated a conservative coalescing heuristic that preserves colorability. But Briggs's algorithm is *too* conservative and leaves too many move instructions in our programs. We show how to interleave coloring reductions with Briggs's coalescing heuristic, leading to an algorithm that is safe but much more aggressive.

Categories and Subject Descriptors: D.3.4 [**Programming Languages**]: Processors—*code generation; optimization*; G.2 [**Discrete Mathematics**]: Graph Theory—*graph algorithms*

General Terms: Algorithms, Languages
Additional Key Words and Phrases: Copy propagation, graph coloring, register allocation, register coalescing

1. INTRODUCTION

Graph coloring is a powerful approach to register allocation and can have a significant impact on the execution of compiled code. A good register allocator does copy propagation, eliminating many move instructions by "coloring" the source temporary and target temporary of a move with the same register. Having copy propagation in the register allocator often simplifies code generation. The generation of target machine code can make liberal use of temporaries, and function call setup can naively move actuals into their formal parameter positions, leaving the register allocator to minimize the moves involved.

Optimizing compilers can generate a large number of move instructions. In static single-assignment (SSA) form [Cytron et al. 1991], each variable in the intermediate form may be assigned into only once. To satisfy this invariant, each program variable is split into several different temporaries that are live at different times. At

Author's address: L. George, Room 2A-426, 600 Mountain Ave, Murray Hill, NJ 07974; email: Lal.George@bell-labs.com; A. W. Appel, Department of Computer Science, Princeton, NJ 08544-2087; email: appel@princeton.edu.

a join point of program control flow, one temporary is copied to another as specified by a "ϕ-function." The SSA transformation allows efficient program optimization, but for good performance these artificial moves must later be removed.

Even non-SSA-based compilers may generate a large number of move instructions. At a procedure call, a caller copies actual parameters to formals; then upon entry to the procedure, the callee moves formal parameters to fresh temporaries. The formal parameters themselves need not be fixed by a calling convention; if a function is local, and all its call sites are identifiable, the formals may be temporaries to be colored (assigned to machine registers) by a register allocator [Kranz et al. 1986]. Again, copy propagation is essential.

Copy propagation tends to produce a graph with temporaries of higher degree (that are live at the same time as a greater number of other temporaries). This can lead to graphs that are uncolorable, so that many temporaries must be spilled to memory. Briggs et al. [1994] show a conservative coalescing algorithm that can do some copy propagation without causing any spilling. But we have found in practice that their algorithm is too conservative, leaving far too many copy instructions in the program.

Our new result can be stated concisely: interleaving Chaitin-style simplification steps with Briggs-style conservative coalescing eliminates many more move instructions than Briggs's algorithm, while still guaranteeing not to introduce spills. Consider the interference graph of Figure 2. Briggs's *conservative coalescing* heuristic, as we will explain, cannot coalesce the move-related pair `j` and `b`, or the pair `d` and `c`, because each pair is adjacent to too many high-degree nodes. Our new algorithm first simplifies the graph, resulting in the graph of Figure 3(a). Now each move-related pair can be safely coalesced, because simplification has lowered the degree of their neighbors.

With our new algorithm, the compiler is free to generate temporaries and copies freely, knowing that almost all copies will be coalesced back together. These copies can be generated based on static single-assignment form, continuation-passing style [Kranz et al. 1986], or other transformations.

2. GRAPH-COLORING REGISTER ALLOCATION

Chaitin et al. [Chaitin 1982; Chaitin et al. 1981] abstracted the register allocation problem as a graph-coloring problem. Nodes in the graph represent *live ranges* or temporaries used in the program. An edge connects any two temporaries that are simultaneously live at some point in the program, that is, whose live ranges *interfere*. The graph-coloring problem is to assign colors to the nodes such that two nodes connected by an edge are not assigned the same color. The number of colors available is equal to the number of registers available on the machine. K-coloring a general graph is NP-complete [Garey and Johnson 1979], so a polynomial-time approximation algorithm is used.

There are five principal phases in a Chaitin-style graph-coloring register allocator:

(1) *Build:* construct the interference graph. Dataflow analysis is used to compute the set of registers that are simultaneously live at a program point, and an edge is added to the graph for each pair of registers in the set. This is repeated for all program points.

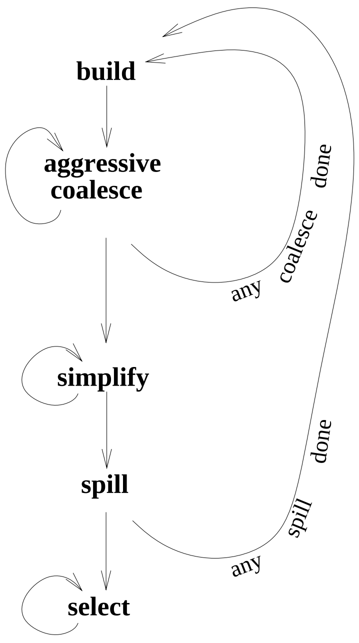


Fig. 1. Flowchart of Chaitin graph-coloring algorithm.

(2) *Coalesce:* remove unnecessary move instructions. A move instruction can be deleted from the program when the source and destination of the move instruction do not have an edge in the interference graph. In other words, the source and destination can be coalesced into one node, which contains the combined edges of the nodes being replaced. When all possible moves have been coalesced, rebuilding the interference graph for the new program may yield further opportunities for coalescing. The build-coalesce phases are repeated until no moves can be coalesced.

(3) *Simplify:* color the graph using a simple heuristic [Kempe 1879]. Suppose the graph G contains a node m with fewer than K neighbors, where K is the number of registers on the machine. Let G' be the graph $G - \{m\}$ obtained by removing m. If G' can be colored, then so can G, for when adding m to the colored graph G' the neighbors of m have at most $K - 1$ colors among them; so a free color can always be found for m. This leads naturally to a stack-based algorithm for coloring: repeatedly remove (and push on a stack) nodes of degree less than K. Each such simplification will decrease the degrees of other nodes, leading to more opportunity for simplification.

(4) *Spill:* but suppose at some point during simplification the graph G has nodes only of *significant degree*, that is, nodes of degree $\geq K$. Then the *simplify* heuristic fails, and a node is marked for spilling. That is, we choose some node in the graph (standing for a temporary variable in the program) and decide to represent it in memory, not registers, during program execution. An optimistic approximation to the effect of spilling is that the spilled node does not interfere

with any of the other nodes remaining in the graph. It can therefore be removed and the simplify process continued. In fact, the spilled node must be fetched from memory just before each use; it will have several tiny live ranges. These will interfere with other temporaries in the graph. If, during a simplify pass, one or more nodes are marked for spilling, the program must be rewritten with explicit fetches and stores, and new live ranges must be computed using dataflow analysis. Then the *build* and *simplify* passes are repeated. This process iterates until *simplify* succeeds with no spills; in practice, one or two iterations almost always suffice.

(5) *Select:* assigns colors to nodes in the graph. Starting with the empty graph, the original graph is built up by repeatedly adding a node from the top of the stack. When a node is added to the graph, there must be a color for it, as the premise for it being removed in the simplify phase was that *it could always be assigned a color provided the remaining nodes in the graph could be successfully colored.*

Figure 1 shows the flowchart for the Chaitin graph-coloring register allocator [Chaitin 1982; Chaitin et al. 1981].

An example program and its interfererence graph is shown in Figure 2. The nodes are labeled with the temporaries they represent, and there is an edge between two nodes if they are simultaneously live. For example, nodes `d`, `k`, and `j` are all connected since they are live simultaneously at the end of the block. Assuming that there are four registers available on the machine, then the simplify phase can start with the nodes `g`, `h`, `c`, and `f` in its working set, since they have less than four neighbors each. A color can always be found for them if the remaining graph can be successfully colored. If the algorithm starts by removing `h` and `g`, and all their edges, then node `k` becomes a candidate for removal and can be added to the worklist. Figure 3(a) shows the state of the graph after nodes `g`, `h`, and `k` have been removed. Continuing in this fashion, we find that one possible order in which nodes can be removed is represented by the stack in Figure 3(b), where the stack grows upward.

The nodes are now popped off the stack and the original graph reconstructed and colored simultaneously. Starting with `m`, a color is chosen arbitrarily, since the graph at this point consists of a singleton node. The next node to be put into the graph is `c`. The only constraint is that it be given a color different from `m`, since there is an edge from `m` to `c`. When the original graph has been fully reconstructed, we have a complete assignment of colors; one possible assignment is shown in Figure 3(c).

3. COALESCING

It is easy to eliminate redundant move instructions with an interference graph. If there is no edge in the interference graph between the source and destination of a move instruction, then the move can be eliminated. The source and destination nodes are coalesced into a new node whose edges are the union of those of the nodes being replaced.

Chaitin [1982] coalesced any pair of nodes not connected by an interference edge. This aggressive form of copy propagation is very successful at eliminating move instructions. Unfortunately, the node being introduced is usually more constrained

```
liveIn: k j
   g := mem[j+12]
   h := k - 1
   f := g * h
   e := mem[j+8]
   m := mem[j+16]
   b := mem[f]
   c := e + 8
   d := c
   k := m + 4
   j := b
   goto d
liveOut: d k j
```

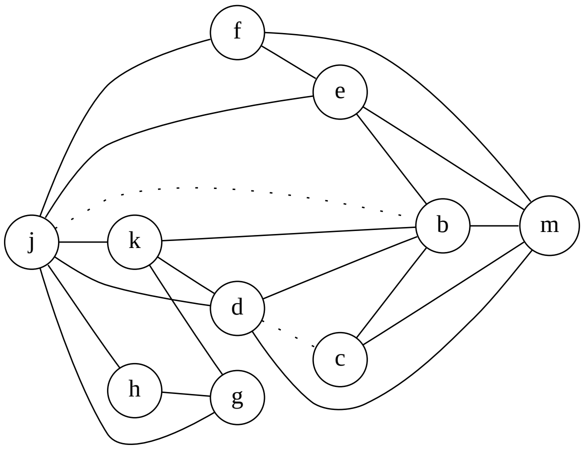
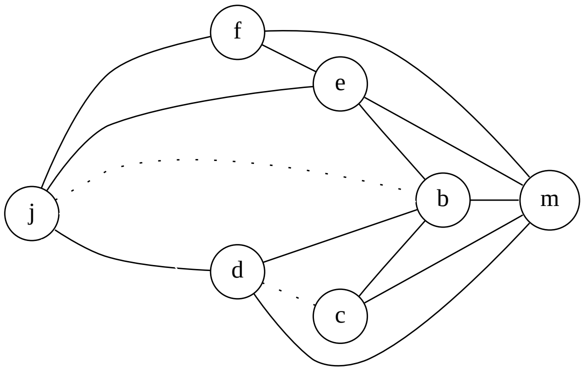


Fig. 2. Interference graph. Dotted lines are not interference edges but indicate move instructions.



(a)

stack	assignment
m	1
c	3
b	2
f	2
e	4
j	3
d	4
k	1
h	2
g	4

(b) (c)

Fig. 3. (a) the intermediate graph after removal of nodes h, g, and k; (b) the stack after all nodes have been removed; and (c) a possible assignment of colors.

than those being removed, as it contains a union of edges. Thus, it is quite possible that a graph, colorable with K colors before coalescing, may no longer be K-colorable after reckless coalescing.

If some nodes are "precolored"—assigned to specific machine registers before register allocation (because they are used in calling conventions, for example)—they cannot be spilled. Some coloring problems with precolored nodes have no solution: if a temporary interferes with K precolored nodes (all of different colors), then the temporary must be spilled. But there is no register into which it can be fetched back for computation! We say such a graph is uncolorable, and we have found that reckless coalescing often leads to uncolorable graphs. Most compilers have a few precolored nodes, used in standard calling conventions, but significantly fewer than K of them; our compiler can potentially precolor all registers for parameter passing, and therefore we *cannot* use reckless coalescing.

Briggs et al. [1994] describe a *conservative* coalescing strategy that addresses this problem. If the node being coalesced has fewer than K neighbors of *significant* degree, then coalescing is guaranteed not to turn a K-colorable graph into a non-K-colorable graph. A node of significant degree is one with K or more neighbors. The proof of the guarantee is simple: after the simplify phase has removed all the insignificant-degree nodes from the graph, the coalesced node will be adjacent only to those neighbors that were of significant degree. Since these are less than K in number, *simplify* can remove the coalesced node from the graph. Thus if the original graph was colorable, the conservative coalescing strategy does not alter the colorability of the graph.

The strategy is conservative because a graph might still have been colorable when a coalesced node has more than K neighbors of significant degree—two of the neighbors might get the same color.

Conservative coalescing is successful at removing many move instructions without introducing spills (stores and fetches), but Briggs found that some moves still remain. For these he used a *biased coloring* heuristic during the *select* phase: when coloring a temporary X that is involved in a move instruction $X \leftarrow Y$ or $Y \leftarrow X$ where Y is already colored, the color of Y is selected if possible. Or, if Y is not yet colored, then a color is chosen that might later be eligible for the coloring of Y. If X and Y can be given the same color (assigned to the same register), then no move instruction will be necessary.

In Figure 2 nodes `c`, `d`, `b`, and `j` are the operands of move instructions. Using the conservative coalescing strategy, these nodes cannot be coalesced. Coalescing `b` and `j` would produce a node with four significant-degree neighbors, namely `m`, `d`, `e`, and `k`. However, during the selection phase it is possible to bias the coloring so that these nodes get the same color. Therefore when coloring `j`, the color of `b` is given preference. If `b` has not been colored yet, then an attempt is made to avoid coloring `j` with a color used by a neighbor of `b`, to enhance the possibility of later coloring `b` the same as `j`.

The success of biased color selection is based on chance. In our example, `b` happened to be colored first with the register `r2`, and `f` was also assigned the same register, thus prohibiting the choice of `r2` for node `j`. Therefore, the move between `b` and `j` cannot be eliminated. If `f` had been assigned another register, then the move could have been eliminated. This type of lookahead is expensive. For similar

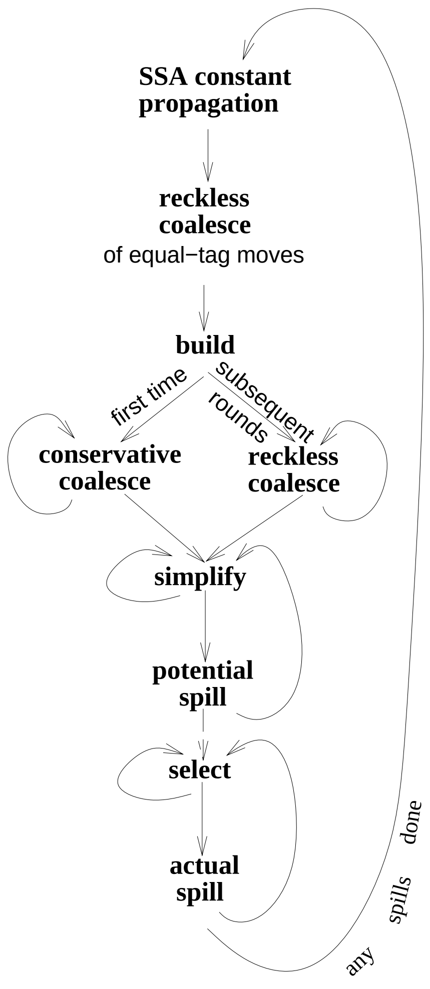


Fig. 4. Briggs's algorithm.

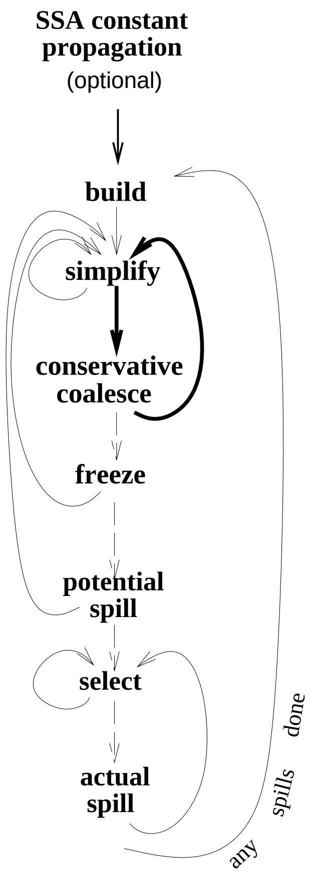


Fig. 5. Iterated algorithm.

reasons the move between `c` and `d` cannot be eliminated. In the example of Figure 2 none of the moves were eliminated using either conservative coalescing or biased selection.

Figure 4 shows the flow of control in Briggs's register allocator. The *potential-spill* and *actual-spill* phases are related to "optimistic coloring," discussed in Section 5.1.

Rematerialization. Briggs et al. observe that variables with constant values can be spilled very cheaply: no store is necessary, and at each use the value may be reloaded or recomputed. Therefore, such variables are good candidates for spilling, and the spill selection algorithm should be informed by the results of a good constant-propagation algorithm. This technique is equally useful in the context of our new algorithm; we have no novel spilling techniques, and all the known heuristics should be applicable.

Briggs also used constant-propagation information in coalescing decisions. When a and b are known to be constant, the move $a \leftarrow b$ will be recklessly coalesced even if the resulting live range would spill; this may be acceptable because the spill is cheap.

In fact, Briggs also recklessly coalesced $a \leftarrow b$ if *neither* a nor b is constant; this is not really justifiable (it can lead to excess spilling), but it was necessary because his conservative coalescing heuristic is too weak to handle huge numbers of moves. Briggs also recklessly coalesced any copy instructions in the original program, leaving only the "splits" induced by ϕ-functions where a and b had inequivalent tags (constant properties) for conservative coalescing.

Our algorithm does not do *any* reckless coalescing, because we cannot afford to with so many precolored nodes; our coalescing is oblivious of constant-propagation information.

4. DIFFICULT COLORING PROBLEMS

Graph-coloring register allocation is now the conventional approach for optimizing compilers. With that in mind, we implemented an optimizer for our compiler (Standard ML of New Jersey [Appel and MacQueen 1991]) that generates many short-lived temporaries with enormous numbers of move instructions. Several optimization techniques contribute to register pressure. We do optimization and register allocation over several procedures at once. Locally defined procedures whose call sites are known can use specially selected parameter temporaries [Appel 1992; Chow 1988; Kranz et al. 1986]. Free variables of nested functions can turn into extra arguments passed in registers [Appel 1992; Kranz et al. 1986]. Type-based representation analysis [Leroy 1992; Shao and Appel 1995] spreads an n-tuple into n separate registers, especially when used as a procedure argument or return value. Callee-save register allocation [Chow 1988] and callee-save closure analysis [Appel and Shao 1992; Shao and Appel 1994] spread the calling context into several registers.

Our earlier phases have some choice about the number of simultaneously live variables they create. For example, representation analysis can avoid expanding large n-tuples; closure analysis can limit the number of procedure parameters representing free variables; and callee-save register allocation can use a limited number of registers. In all these cases, our optimization phases are guided by the number of registers available on the target machine. Thus, although they never assign registers explicitly, they tend to produce register allocation problems that are as hard as possible, but no harder: spilling is rarely needed, yet there are often $K - 1$ live variables.

In implementing these optimization techniques, we assumed that the graph-coloring register allocator would be able to eliminate "all" the move instructions and assign registers without too much spilling. But instead we found that Chaitin's reckless coalescing produced too many spills, and Briggs's conservative coalescing left too many move instructions. It seems that our register allocation and copy propagation problems are more difficult than those produced by the Fortran compilers measured by Briggs.

Our measurements of realistic programs show that conservative coalescing eliminates only 24% of the move instructions; biased selection eliminates a further 39% (of the original moves), leaving 37% of the moves in the program. Our new algorithm eliminates all but 16% of the move instructions. This results in a speedup of 4.4% over programs compiled using one-round conservative coalescing and biased selection.

Compilers that generate few temporaries, or that do copy propagation entirely before register allocation, will not see such an improvement from our algorithm; but these compilers are not able to take advantage of the tradeoff between copy propagation and spilling. With our new algorithm, compilers can integrate copy propagation with register allocation to use registers more effectively without unnecessary moves or spills.

5. ITERATED REGISTER COALESCING

Interleaving Chaitin-style simplification steps with Briggs-style conservative coalescing eliminates many more move instructions than Briggs's algorithm, while still guaranteeing not to introduce spills.

Our new approach calls the coalesce and simplify procedures in a loop, with *simplify* called first. The building blocks of the algorithm are essentially the same, but with a different flow of control shown in Figure 5. Our main contribution is the dark backward arrow. There are five principal phases in our register allocator:

(1) *Build:* construct the interference graph, and categorize each node as being either *move related* or not. A move-related node is one that is either the source or destination of a move instruction.

(2) *Simplify:* one at a time, remove non-move-related nodes of low degree from the graph.

(3) *Coalesce:* perform Briggs-style conservative coalescing on the reduced graph obtained in the simplification phase. Since the degrees of many nodes have been reduced by *simplify*, the conservative strategy is likely to find many more moves to coalesce than it would have in the initial interference graph. After two nodes have been coalesced (and the move instruction deleted), if the resulting node is no longer move related it will be available for the next round of simplification. *Simplify* and *Coalesce* are repeated until only significant-degree or move-related nodes remain.

(4) *Freeze:* if neither *simplify* nor *coalesce* applies, we look for a move-related node of low degree. We *freeze* the moves in which this node is involved: that is, we give up hope of coalescing those moves. This causes the node (and perhaps other nodes related to the frozen moves) to be considered not move related. Now, *simplify* and *coalesce* are resumed.

(5) *Select:* same as before. Unlike Briggs, we do not use biased selection, although it is conceivable that some of the frozen moves could be eliminated through biased selection.

The Appendix shows the algorithm in pseudocode.

Consider the initial interference graph shown in Figure 2. Nodes `b`, `c`, `d`, and `j` are the only move-related nodes in the graph. The initial worklist used in the

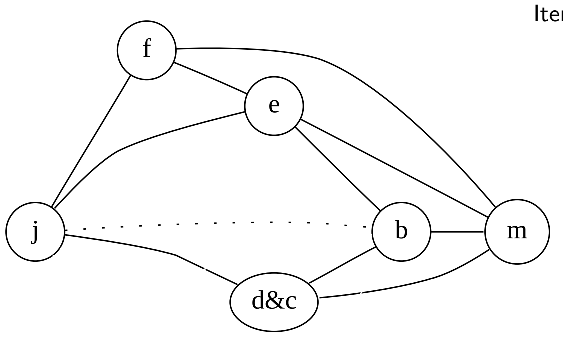


Fig. 6. Interference graph after coalescing d and c.

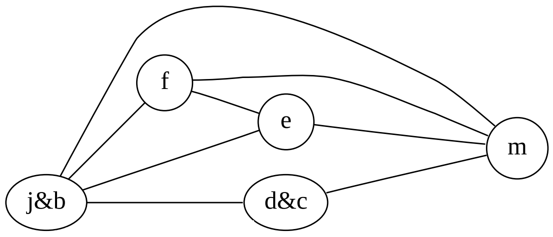


Fig. 7. Interference graph after coalescing b and j.

simplify phase must contain only non-move-related nodes and consists of nodes `g`, h, and `f`. Node `c` is not included, as it is move related. Once again, after removal of `g`, `h`, and `k` we obtain the graph in Figure 3(a).

We could continue the simplification phase further; however, if we invoke a round of coalescing at this point, we discover that `c` and `d` are indeed coalescable, as the coalesced node has only two neighbors of significant degree — namely, `m` and `b`. The resulting graph is shown in Figure 6, with the coalesced node labeled as `d&c`.

From Figure 6 we see that it is possible to coalesce `b` and `j` as well. Nodes `b` and `j` are adjacent to two neighbors of significant degree—namely, `m` and `e`. The result of coalescing `b` and `j` is shown in Figure 7.

After coalescing these two moves, there are no more move-related nodes, and therefore no more coalescing possible. The simplify phase can be invoked one more time to remove all the remaining nodes. A possible assignment of colors is shown below:

e	1
m	2
f	3
j&b	4
d&c	1
k	2
h	2
g	1
stack	coloring

This coloring is a valid assignment for the original graph in Figure 2.

THEOREM. *Assume an interference graph G is colorable using the simplify heuris-*

tic. Conservative coalescing on an intermediate graph that is produced after some rounds of simplification of G produces a colorable graph.

PROOF. Let a simplified graph G' be one in which some or all low-degree, non-move-related nodes of G and their edges have been removed. Nodes that have been removed from a graph G cannot affect the colors of nodes that remain in G'. Indeed, they are colored after all nodes in G' have been colored. Therefore, conservative coalescing applied to two nodes in G' cannot affect the colorability of the original graph G. □

This technique is very successful: the first round of simplification removes such a large percentage of nodes that the conservative coalescing phase can usually be applied to all the move instructions in one pass.

Some moves are neither coalesced nor frozen. Instead, they are *constrained.* Consider the graph X, Y, Z, where (X, Z) is the only interference edge, and there are two moves $X \leftarrow Y$ and $Y \leftarrow Z$. Either move is a candidate for coalescing. But after X and Y are coalesced, the remaining move $XY \leftarrow Z$ cannot be coalesced because of the interference edge (XY, Z). We say this move is *constrained*, and we remove it from further consideration: it no longer causes nodes to be treated as move related.

5.1 Pessimistic or Optimistic Coloring

Briggs et al. [1994] introduced *optimistic coloring*, which reduces the number of spills generated. In the *simplify* phase, when there are no low-degree nodes, instead of marking a node for spilling they just remove it from the graph and push it on the stack. This is a *potential spill.* Then the *select* phase may find that there is no color for the node; this is an *actual spill.* But in some cases *select* may find a color because the K (or more) neighbors will be colored with fewer than K distinct colors.

Our algorithm is compatible with either pessimistic or optimistic coloring. With Chaitin's pessimistic coloring, we guarantee not to introduce new spills. With optimistic coloring, we can only guarantee not to increase the number of *potential* spills; the number of actual spills might change.

If spilling is necessary, *build* and *simplify* must be repeated on the whole program. The simplest version of our algorithm discards any coalescings found if *build* must be repeated. Then it is easy to prove that coalescing does not increase the number of spills in any future round of *build.*

However, coalescing significantly reduces the number of temporaries and instructions in the graph, which would speed up the subsequent rounds of *build* and *simplify.* It is safe to keep any coalescings done before the first spill node is removed from the graph. In the case of optimistic coloring, this means the first *potential* spill. Since many coalesces occur before the first spill, the graph used in subsequent rounds will be much smaller; this makes the algorithm run significantly faster. (The algorithm we show in the appendix is a simpler variant that discards all coalesces in the event of a spill.)

6. GRAPH-COLORING IMPLEMENTATION

The main data structure used to implement graph coloring is the adjacency list representation of the interference graph. During the selection phase, the adjacency list is used to derive the list of neighbors that have already been colored, and during coalescing, two adjacency lists are unioned to form the coalesced node.

Chaitin and Briggs use a bit-matrix representation of the graph (that gives constant time membership tests) in addition to the adjacency lists. Since the bit matrix is symmetrical, they represent only one half of the matrix, so the number of bits required is $n(n+1)/2$. In practice, n can be large (for us it is often over 4000), so the bit-matrix representation takes too much space. We take advantage of the fact that the matrix is sparse and use a hash table of integer pairs. For a typical average degree of 16 and for $n = 4000$, the sparse table takes 256KB (2 words per entry), and the bit matrix would take 1MB.

Some of our temporaries are “precolored,” that is, they represent machine registers. The front end generates these when interfacing to standard calling conventions across module boundaries, for example. Ordinary temporaries can be assigned the same colors as precolored registers, as long as they do not interfere, and in fact this is quite common. Thus, a standard calling-convention register can be reused inside a procedure as a temporary.

The adjacency lists of machine registers are very large (see Figure 9); because they are used in standard calling conventions they interfere with many temporaries. Furthermore, since machine registers are precolored, their adjacency lists are not necessary for the *select* phase. Therefore, to save space and time we do not explicitly represent the adjacency lists of the machine registers. The time savings is significant: when X is coalesced to Y, and X interferes with a machine register, then the long adjacency list for the machine register must be traversed to remove X and add Y.

In the absence of adjacency lists for machine registers, a simple heuristic is used to coalesce pseudoregisters with machine registers. A pseudoregister X can be coalesced to a machine register R, if for every T that is a neighbor of X, the coalescing does not increase the number of T's significant-degree neighbors from $< K$ to $\geq K$.

Any of the following conditions will suffice:

(1) T already interferes with R. Then the set of T's neighbors gains no nodes.

(2) T is a machine register. Since we already assume that all machine registers mutually interfere, this implies condition (1).

(3) Degree(T) $< K$. Since T will lose the neighbor X and gain the neighbor R, then degree(T) will continue to be $< K$.

The third condition can be weakened to require T has fewer than $K-1$ neighbors of significant degree. This test would coalesce more liberally while still ensuring that the graph retains its colorability; but it would be more expensive to implement.

Associated with each move-related node is a count of the moves it is involved in. This count is easy to maintain and is used to test if a node is no longer move related. Associated with all nodes is a count of the number of neighbors currently in the graph. This is used to determine whether a node is of significant

Benchmark	Lines	Type	Description
knuth-bendix	580	Symbolic	The Knuth-Bendix completion algorithm
vboyer	924	Symbolic	The Boyer-Moore theorem prover using vectors
mlyacc	7422	Symbolic	A parser generator, processing the SML grammar
nucleic	2309	F.P.	Nucleic acid 3D structure determination
simple	904	F.P.	A spherical fluid-dynamics program
format	2456	F.P.	SML/NJ formatting library
ray	891	F.P.	Ray tracing

Fig. 8. Benchmark description.

Benchmark	**live ranges**		**average degree**		**instructions**	
	machine	pseudo	machine	pseudo	moves	nonmoves
knuth-bendix	15	5360	1296	13	4451	9396
vboyer	12	9222	4466	10	1883	20097
mlyacc:						
yacc.sml	16	6382	1766	12	5258	12123
utils.sml	15	3494	1050	14	2901	6279
yacc.grm.sml	19	4421	1346	11	2203	9606
nucleic	15	9825	4791	46	1621	27554
simple	19	10958	2536	15	8249	21483
format	16	3445	652	13	2785	6140
ray	15	1330	331	16	1045	2584

Fig. 9. Benchmark characteristics

degree during coalescing and whether a node can be removed from the graph during simplification.

To make the algorithm efficient, it is important to be able to quickly perform each *simplify* step (removing a low-degree non-move-related node), each *coalesce* step, and each *freeze* step. To do this, we maintain four work lists:

—Low-degree non-move-related nodes (*simplifyWorklist*);

—Coalesce candidates: move-related nodes that have not been proved uncoalesceable (*worklistMoves*);

—Low-degree move-related nodes (*freezeWorklist*).

—High-degree nodes (*spillWorklist*).

Maintenance of these worklists avoids quadratic time blowup in finding coalesceable nodes. Chaitin keeps unspillable nodes (such as the tiny live ranges resulting from previous spills) in a separate list to decrease the cost of searching for a spill candidate; perhaps the spillWorkList should even be a priority queue based on spill cost divided by node degree.

When a node `X` changes from significant to low degree, the moves associated with its neighbors must be added to the move worklist. Moves that were blocked with too many significant neighbors (including `X`) might now be enabled for coalescing. Moves are added to the move worklist in only a few places:

—During simplify the degree of a node X might make the transition as a result of removing another node. Moves associated with neighbors of X are added to the *worklistMoves*.

—When coalescing U and V, there may be a node X that interferes with both U and V. The degree of X is decremented, as it now interferes with the single coalesced node. Moves associated with neighbors of X are added. If X is move related, then moves associated with X itself are also added, as both U and V may have been significant-degree nodes.

—When coalescing U to V, moves associated with U are added to the move worklist. This will catch other moves from U to V.

7. BENCHMARKS

For our measurements we used seven Standard ML programs and SML/NJ compiler version 108.3 running on a DEC Alpha. A short description of each benchmark is given in Figure 8. Five of the benchmarks use floating-point arithmetic—namely, `nucleic`, `simple`, `format`, and `ray`.

Some of the benchmarks consist of a single module, whereas others consist of multiple modules spread over multiple files. For benchmarks with multiple modules, we selected a module with a large number of live ranges. For the *mlyacc* benchmarks we selected the modules defined in the files `yacc.sml`, `utils.sml`, and `yacc.grm.sml`.

Each program was compiled to use six callee-save registers. This is an optimization level that generates high register pressure and very many move instructions. Previous versions of SML/NJ used only three callee-save registers, because their copy-propagation algorithms had not been able to handle six effectively.

Figure 9 shows the characteristics of each benchmark. Statistics of the interference graph are separated into those associated with machine registers and those with pseudoregisters. *Live ranges* shows the number of nodes in the interference graph. For example, the `knuth-bendix` program mentions 15 machine registers and 5360 pseudoregisters. These numbers are inflated as the algorithm is applied to all the functions in the module at one time; in practice the functions would be applied to connected components of the call graph. The *average degree* column, indicating the average length of adjacency lists, shows that the length of adjacencies associated with machine registers is orders of magnitude larger than those associated with pseudoregisters. The last two columns show the total number of move and nonmove instructions.

8. RESULTS

Ideally, we would like to compare our algorithm directly against Chaitin's or Briggs's. However, since our compiler uses many precolored nodes, and Chaitin's and Brigg's algorithms both do reckless coalescing (Chaitin's more than Briggs's), both of these algorithms would lead to uncolorable graphs.

What we have done instead is choose the *safe* parts of Brigg's algorithm—the early one-round conservative coalescing and the biased coloring—to compare against our algorithm. We omit from Brigg's algorithm the reckless coalescing of same-tag splits.

Benchmark	**Nodes spilled**	**Instructions** store	fetch
knuth-bendix	0	0	0
vboyer	0	0	0
yacc.sml	0	0	0
utils.sml	17	17	35
yacc.grm.sml	24	24	33
nucleic	701	701	737
simple	12	12	24
format	0	0	0
ray	6	6	10

Fig. 10. Spill statistics.

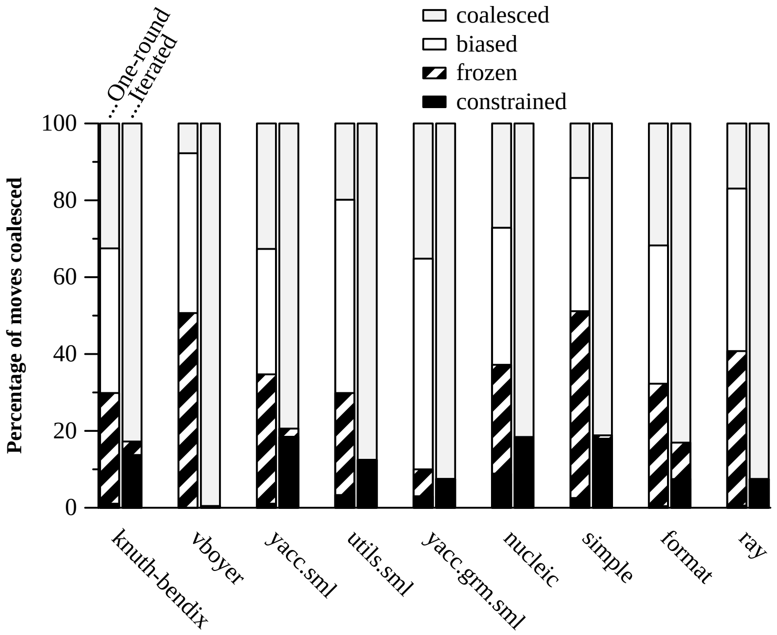


Fig. 11. Comparison of moves coalesced by two algorithms. The black and striped, labeled *frozen* and *constrained*, represent moves remaining in the program.

From both algorithms (ours and Brigg's) we omit optimistic coloring and cheap spilling of constant values (rematerialization); these would be useful in either algorithm, but their absence should not affect the comparison.

We will call the two algorithms *one-round coalescing* and *iterated coalescing.*

Figure 10 shows the spilling statistics. The number of spills—not surprisingly—is identical for both the iterated and Briggs's scheme. Most benchmarks do not spill at all. From among the programs that contain spill code, the number of *store* instructions is almost equal to the number of *fetch* instructions, suggesting that the nodes that have been spilled may have just one definition and use.

Figure 11 compares the one-round and iterated algorithms on the individual

Benchmark	coalesced	constrained	biased	freeze	% coalesced
knuth-bendix	1447	47	1675	1282	70%
vboyer	146	0	783	954	49
mlyacc:					
yacc.sml	1717	56	1716	1769	65
utils.sml	576	96	1459	770	70
yacc.grm.sml	775	66	1208	154	90
nucleic	440	144	578	459	63
simple	1170	209	2860	4010	49
format	884	12	1002	887	68
ray	177	6	442	420	59

Fig. 12. Coalesce statistics for one-round coalescing algorithm

Benchmark	coalesced	constrained	freeze	% coalesced
knuth-bendix	3684	611	156	83%
vboyer	1875	8	0	99
mlyacc:				
yacc.sml	4175	971	112	79
utils.sml	2539	362	0	88
yacc.grm.sml	2038	165	0	93
nucleic	1323	298	0	82
simple	6695	1482	72	81
format	2313	208	264	83
ray	967	78	0	93

Fig. 13. Coalescing statistics for iterated register allocator.

benchmarks.

Referring to the bar charts for the one-round coalescing algorithm: *coalesced* are the moves removed using the conservative coalescing strategy; *constrained* are the moves that become constrained by having an interference edge added to them as a result of some other coalesce; *biased* are the moves coalesced using biased selection, and *frozen* are the moves that could not be coalesced using biased selection. On an average 24% of the nodes are removed in the coalesce phase, and all the rest are at the mercy of biased selection. Considering all benchmarks together, 62% of all moves are removed.

For the iterated scheme *coalesced* and *constrained* have the same meaning as above, but *frozen* refers to the moves chosen by the *Freeze* heuristic. Biased selection is not needed, so *biased* does not apply. More than 84% of all moves are removed with the new algorithm. Figures 12 and 13 give more detailed numbers.

The average improvement in code size is 5% (Figure 14). Since moves are the very fastest kind of instruction, we would expect that the improvement in speed would not be nearly this large. But taking the average timing from a series of 40 runs, we measured a surprising speedup average of 4.4% using the iterated scheme over one-round coalescing. Probably many of the coalesced moves are inside frequently executed loops.

Figure 15 shows the timings on the individual benchmarks. Each entry is the average of the sum of user, system, and garbage collection time. We believe that the significant speed improvement is partly due to the better I-cache performance

Fig. 14. Code size.

Benchmark	One round	Iterated	Improvement
knuth-bendix	42900	40652	5%
vboyer	84204	80420	4
yacc.sml	55792	52824	5
utils.sml	28580	26564	7
yacc.grm.sml	39304	39084	1
nucleic	112628	111408	1
simple	102808	92148	10
format	28156	26448	6
ray	12040	10648	11
Average			5%

Fig. 15. Execution speed.

Benchmark	One round	Iterated	Improvement
knuth-bendix	7.11	6.99	2%
vboyer	2.35	2.30	2
mlyacc	3.30	3.18	3
nucleic	2.91	2.59	11
simple	27.72	27.51	1
format	8.87	8.73	2
ray	49.04	44.35	10
Average			4.4%

of smaller programs.

There is a significant speed improvement when using six callee-save registers over three. The old register allocator in the SML/NJ compiler showed a degradation in performance when the number of callee-save registers was increased beyond three [Appel and Shao 1992]. Appel and Shao attributed this to poor register targeting (copy propagation). The new compiler using iterated coalescing shows a distinct improvement when going from three to six callee-save registers, confirming Appel and Shao's guess. Use of a better register allocator now allows us to take full advantage of Shao's improved closure analysis algorithm [Shao and Appel 1994]. Figure 16 shows the average execution time taken over 40 runs. All benchmarks show some improvement with more callee-save registers.

It is difficult to compare the compilation speed of our algorithm with Briggs's, since we do not have his allocator as he implemented it. Each round of our algorithm, like his, takes linear time. But his algorithm disables coalescing with machine registers in the first round, requiring an extra round in many cases to coalesce pseudoregisters with machine registers; our algorithm does not.

Fig. 16. Execution time, varying the number of callee-save registers.

	3	6	
Benchmark	**callee-save**	**callee-save**	**Improvement**
knuth-bendix	7.06 sec	6.99	1 %
vboyer	2.40	2.30	4
mlyacc	3.50	3.18	9
simple	28.21	27.51	2
format	8.76	8.73	0
ray	47.20	44.34	6

9. CONCLUSIONS

Alternating the simplify and coalesce phases of a graph-coloring register allocator eliminates many more moves than the older approach of coalescing before simplification. It ought to be easy to incorporate this algorithm into any existing implementation of graph-coloring-based register allocation, as it is easy to implement and uses the same building blocks.

APPENDIX

A. ALGORITHM IN PSEUDOCODE

We give a complete implementation of the algorithm (Figure 5) in pseudocode. In this implementation, all coalescings are abandoned when an actual spill is detected.

A.1 Data Structures

A.1.1 *Node Worklists, Node Sets, and Node Stacks*

—**precolored:** machine registers, preassigned a color. Chaitin handles each live range that must be assigned to machine register r by making a new temporary that interferes with all machine registers except r; we just use a single node precolored with color r directly to implement all such live ranges.
—**initial:** temporary registers, not preassigned a color and not yet processed by the algorithm.
—**simplifyWorklist:** list of low-degree non-move-related nodes.
—**freezeWorklist:** low-degree move-related nodes.
—**spillWorklist:** high-degree nodes.
—**spilledNodes:** nodes marked for spilling during this round; initially empty.
—**coalescedNodes:** registers that have been coalesced; when the move u:=v is coalesced, one of u or v is added to this set, and the other is put back on some worklist.
—**coloredNodes:** nodes successfully colored.
—**selectStack:** stack containing temporaries removed from the graph.

Invariant. These lists and sets are always *mutually disjoint,* and every node is always in exactly one of the sets or lists. Since membership in these sets is often tested, the representation of each node should contain an enumeration value telling which set it is in.

Precondition. Initially (on entry to Main), and on exiting RewriteProgram, only the sets *precolored* and *initial* are nonempty.

A.1.2 *Move Sets..* There are five sets of move instructions:

—**coalescedMoves:** moves that have been coalesced.
—**constrainedMoves:** moves whose source and target interfere.
—**frozenMoves:** moves that will no longer be considered for coalescing.
—**worklistMoves:** moves enabled for possible coalescing.
—**activeMoves:** moves not yet ready for coalescing.

Move Invariant. Every move is in exactly one of these sets (after Build through the end of Main).

A.1.3 *Others*

—**adjSet:** the set of interference edges (u, v) in the graph. If $(u, v) \in$ adjSet then $(v, u) \in$ adjSet. We represent adjSet as a hash table of integer pairs.
—**adjList:** adjacency list representation of the graph; for each nonprecolored temporary u, adjList$[u]$ is the set of nodes that interfere with u.
—**degree:** an array containing the current degree of each node. Precolored nodes are initialized with a degree of ∞, or $(N + K)$ where N is the size of the graph.

Degree Invariant. For any $u \in$ simplifyWorklist $\cup$ freezeWorklist $\cup$ spillWorklist it will always be the case that

$$\begin{aligned}\text{degree}(u) = |\text{adjList}(u) \ \cap \ (&\text{precolored} \cup \text{simplifyWorklist} \\ &\cup \text{freezeWorklist} \cup \text{spillWorklist})|\end{aligned}$$

—**moveList:** a mapping from node to the list of moves it is associated with.
—**alias:** when a move (u, v) has been coalesced, and v put in coalescedNodes, then alias$(v) = u$.
—**color:** the color chosen by the algorithm for a node. For precolored nodes this is initialized to the given color.

simplifyWorklist Invariant.

$$\begin{aligned}&(u \in \text{simplifyWorklist}) \ \Rightarrow \\ &\quad \text{degree}(u) < K \ \wedge \ \text{moveList}[u] \cap (\text{activeMoves} \cup \text{worklistMoves}) = \{\}\end{aligned}$$

freezeWorklist Invariant.

$$\begin{aligned}&(u \in \text{freezeWorklist}) \ \Rightarrow \\ &\quad \text{degree}(u) < K \ \wedge \ \text{moveList}[u] \cap (\text{activeMoves} \cup \text{worklistMoves}) \neq \{\}\end{aligned}$$

spillWorklist Invariant.

$$(u \in \text{spillWorklist}) \ \Rightarrow \ \text{degree}(u) \geq K$$

A.2 Program Code

```
procedure Main()                                                    Main
    LivenessAnalysis()
    Build()
    MkWorklist()
    repeat
        if simplifyWorklist ≠ {} then Simplify()
        else if worklistMoves ≠ {} then Coalesce()
        else if freezeWorklist ≠ {} then Freeze()
        else if spillWorklist ≠ {} then SelectSpill()
    until simplifyWorklist = {} ∧ worklistMoves = {}
          ∧ freezeWorklist = {} ∧ spillWorklist = {}
    AssignColors()
    if spilledNodes ≠ {} then
        RewriteProgram(spilledNodes)
        Main()
```

The algorithm is invoked using the procedure `Main`, which loops (via tail recursion) until no spills are generated.

If `AssignColors` produces spills, then `RewriteProgram` allocates memory locations for the spilled temporaries and inserts store and fetch instructions to access them. These stores and fetches are to newly created temporaries (albeit with tiny live ranges), so the Main loop must be performed on the altered graph.

```
procedure AddEdge($u$, $v$)                                        AddEdge
    if $((u, v) \notin$ adjSet$)\ \wedge (u <> v)$ then
        adjSet := adjSet $\cup \{(u, v), (v, u)\}$
        if $u \notin$ precolored then
            adjList[$u$] := adjList[$u$] $\cup \{v\}$
            degree[$u$] := degree[$u$] + 1
        if $v \notin$ precolored then
            adjList[$v$] := adjList[$v$] $\cup \{u\}$
            degree[$v$] := degree[$v$] + 1
```

```
procedure Build ()                                                 Build
    forall $b \in$ blocks in program
        let live = liveOut($b$)
        forall $I \in$ instructions($b$) in reverse order
            if isMoveInstruction($I$) then
                live := live$\setminus$use($I$)
                forall $n \in$ def($I$) $\cup$ use($I$)
                    moveList[$n$] := moveList[$n$] $\cup \{I\}$
                worklistMoves := worklistMoves $\cup \{I\}$
            live := live $\cup$ def($I$)
            forall $d \in$ def($I$)
                forall $l \in$ live
                    AddEdge($l$, $d$)
            live := use($I$) $\cup$ (live$\setminus$def($I$))
```

Procedure `Build` constructs the interference graph and bit matrix. We use the sparse set representation described by Briggs and Torczon [1993] to implement the variable `live`. `Build` only adds an interference edge between a node that is defined at some point and the nodes that are currently live at that point. It is not necessary to add interferences between nodes in the live set. These edges will be added when processing other blocks in the program.

Move instructions are given special consideration. It is important not to create artifical interferences between the source and destination of a move. Consider the program:

```
t := s              ; copy
...
x := ... s ...      ; use of s
...
y := ... t ...      ; use of t
```

After the copy instruction both `s` and `t` are live, and an interference edge would be added between `s` and `t`, since `t` is being defined at a point where `s` is live. The solution is to temporarily remove `s` from the live set and continue. The pseudocode described by Briggs and Torczon [1993] contains a bug, where `t` is removed from the live set instead of `s`.

The `Build` procedure also initializes the `worklistMoves` to contain all the moves in the program.

```
function Adjacent($n$)                                                    *Adjacent*
    adjList[$n$] $\setminus$ (selectStack $\cup$ coalescedNodes)

function NodeMoves ($n$)                                                  *NodeMoves*
    moveList[$n$] $\cap$ (activeMoves $\cup$ worklistMoves)

function MoveRelated($n$)                                                 *MoveRelated*
    NodeMoves($n$) $\neq \{\}$

procedure MkWorklist()                                                    *MkWorklist*
    forall $n \in$ initial
        initial := initial $\setminus \{n\}$
        if degree[$n$] $\geq K$ then
            spillWorklist := spillWorklist $\cup$ {n}
        else if MoveRelated($n$) then
            freezeWorklist := freezeWorklist $\cup$ {n}
        else
            simplifyWorklist := simplifyWorklist $\cup$ {n}

procedure Simplify()                                                      *Simplify*
    let $n \in$ simplifyWorklist
    simplifyWorklist := simplifyWorklist $\setminus \{n\}$
    push($n$, selectStack)
    forall m $\in$ Adjacent($n$)
        DecrementDegree($m$)

procedure DecrementDegree($m$)                                            *DecrementDegree*
    let $d$ = degree[$m$]
    degree[$m$] := d-1
    if $d = K$ then
        EnableMoves($\{m\}$ $\cup$ Adjacent($m$))
        spillWorklist := spillWorklist $\setminus \{m\}$
        if MoveRelated($m$) then
            freezeWorklist := freezeWorklist $\cup \{m\}$
        else
            simplifyWorklist := simplifyWorklist $\cup \{m\}$
```

Removing a node from the graph involves decrementing the degree of its *current* neighbors. If the `degree` is already less than $K-1$ then the node must be move related and is not added to the `simplifyWorklist`. When the degree of a node transitions from K to $K-1$, moves associated with its neighbors may be enabled.

```
procedure EnableMoves(nodes)                                              *EnableMoves*
    forall $n \in$ nodes
        forall $m \in$ NodeMoves($n$)
            if $m \in$ activeMoves then
                activeMoves := activeMoves $\setminus \{m\}$
                worklistMoves := worklistMoves $\cup \{m\}$
```

```
procedure Coalesce()                                                  Coalesce
    let $m_{(=copy(x,y))} \in$ worklistMoves
    $x :=$ GetAlias($x$)
    $y :=$ GetAlias($y$)
    if $y \in$ precolored then
        let $(u, v) = (y, x)$
    else
        let $(u, v) = (x, y)$
    worklistMoves := worklistMoves $\setminus \{m\}$
    if $(u = v)$ then
        coalescedMoves := coalescedMoves $\cup \{m\}$
        AddWorkList($u$)
    else if $v \in$ precolored $\vee$ $(u, v) \in$ adjSet then
        constrainedMoves := constrainedMoves $\cup \{m\}$
        addWorkList($u$)
        addWorkList($v$)
    else if $u \in$ precolored $\wedge$ $(\forall t \in$ Adjacent($v$), OK($t, u$))
          $\vee$ $u \notin$ precolored $\wedge$ Conservative(Adjacent($u$) $\cup$ Adjacent($v$)) then
        coalescedMoves := coalescedMoves $\cup \{m\}$
        Combine($u$,$v$)
        AddWorkList($u$)
    else
        activeMoves := activeMoves $\cup \{m\}$
```

Only moves in the `worklistMoves` are considered in the coalesce phase. When a move is coalesced, it may no longer be move related and can be added to the simplify worklist by the procedure `AddWorkList`. `OK` implements the heuristic used for coalescing a precolored register. `Conservative` implements the Briggs conservative coalescing heuristic.

```
procedure AddWorkList(u)                                              AddWorkList
    if ($u \notin$ precolored $\wedge$ not(MoveRelated($u$)) $\wedge$ degree[$u$] $<$ K) then
        freezeWorklist := freezeWorklist $\setminus \{u\}$
        simplifyWorklist := simplifyWorklist $\cup \{u\}$

function OK($t$,$r$)                                                  OK
    degree[$t$] $< K \vee t \in$ precolored $\vee (t, r) \in$ adjSet

function Conservative(nodes)                                          Conservative
    let $k = 0$
    forall $n \in$ nodes
        if degree[$n$] $\geq K$ then $k := k + 1$
    return $(k < K)$

function GetAlias ($n$)                                               GetAlias
    if $n \in$ coalescedNodes then
        GetAlias(alias[$n$])
    else $n$
```

```
procedure Combine(u,v)                                          Combine
    if $v \in$ freezeWorklist then
        freezeWorklist := freezeWorklist $\setminus \{v\}$
    else
        spillWorklist := spillWorklist $\setminus \{v\}$
    coalescedNodes := coalescedNodes $\cup \{v\}$
    alias[$v$] := $u$
    nodeMoves[$u$] := nodeMoves[$u$] $\cup$ nodeMoves[$v$]
    forall $t \in$ Adjacent($v$)
        AddEdge($t$,$u$)
        DecrementDegree($t$)
    if degree[$u$] $\geq K \wedge u \in$ freezeWorkList
        freezeWorkList := freezeWorkList $\setminus \{u\}$
        spillWorkList := spillWorkList $\cup \{u\}$

procedure Freeze()                                              Freeze
    let $u \in$ freezeWorklist
    freezeWorklist := freezeWorklist $\setminus \{u\}$
    simplifyWorklist := simplifyWorklist $\cup \{u\}$
    FreezeMoves($u$)
```

Procedure `Freeze` pulls out a node from the `freezeWorklist` and freezes all moves associated with this node. In principle, a heuristic could be used to select the freeze node. In our experience, freezes are not common, and a selection heuristic is unlikely to make a significant difference.

```
procedure FreezeMoves($u$)                                      FreezeMoves
    forall $m$(= copy(u,v) or copy(v,u)) $\in$ NodeMoves($u$)
        if $m \in$ activeMoves then
            activeMoves := activeMoves $\setminus \{m\}$
        else
            worklistMoves := worklistMoves $\setminus \{m\}$
        frozenMoves := frozenMoves $\cup \{m\}$
        if NodeMoves($v$) = {} $\wedge$ degree[$v$] $< K$ then
            freezeWorklist := freezeWorklist $\setminus \{v\}$
            simplifyWorklist := simplifyWorklist $\cup \{v\}$

procedure SelectSpill()                                         SelectSpill
    let $m \in$ spillWorklist selected using favorite heuristic
        Note: avoid choosing nodes that are the tiny live ranges
        resulting from the fetches of previously spilled registers
    spillWorklist := spillWorklist $\setminus \{m\}$
    simplifyWorklist := simplifyWorklist $\cup \{m\}$
    FreezeMoves($m$)

procedure AssignColors()                                        AssignColors
    while SelectStack not empty
        let $n$ = pop(SelectStack)
        okColors := {0, ..., K-1}
        forall $w \in$ adjList[$n$]
            if GetAlias($w$) $\in$ (coloredNodes $\cup$ precolored) then
                okColors := okColors $\setminus$ {color[GetAlias($w$)]}
        if okColors = {}  then
            spilledNodes := spilledNodes ∪ {n}
        else
            coloredNodes := coloredNodes ∪ {n}
            let c ∈ okColors
            color[n] := c
    forall n ∈ coalescedNodes
        color[n] := color[GetAlias(n)]

procedure RewriteProgram()                                  RewriteProgram
    Allocate memory locations for each v ∈ spilledNodes,
    Create a new temporary v_i for each definition and each use,
    In the program (instructions), insert a store after each
    definition of a v_i, a fetch before each use of a v_i.
    Put all the v_i into a set newTemps.
    spilledNodes := {}
    initial := coloredNodes ∪ coalescedNodes ∪ newTemps
    coloredNodes := {}
    coalescedNodes := {}
```

We show a variant of the algorithm in which all coalesces are discarded if the program must be rewritten to incorporate spill fetches and stores. But as Section 5.1 explains, we recommend keeping all the coalesces found before the first call to `SelectSpill` and rewriting the program to eliminate the coalesced move instructions and temporaries.

ACKNOWLEDGEMENTS

Kenneth Zadeck provided many detailed and insightful criticisms and suggestions about the algorithm. Steven Walk, Chris Fraser, and Kent Wilken gave us feedback on an early draft of the manuscript. Preston Briggs, Max Hailperin, and Luke Blanshard helpfully commented on later drafts.

REFERENCES

Appel, A. W. 1992. *Compiling with Continuations.* Cambridge University Press. ISBN 0-521-41695-7.

Appel, A. W. and MacQueen, D. B. 1991. Standard ML of New Jersey. In *Third Int'l Symp. on Prog. Lang. Implementation and Logic Programming*, M. Wirsing, Ed. Springer-Verlag, New York, 1–13.

Appel, A. W. and Shao, Z. 1992. Callee-save registers in continuation-passing style. *Lisp Symb. Comput. 5,* 3, 191–221.

Briggs, P., Cooper, K. D., and Torczon, L. 1994. Improvements to graph coloring register allocation. *ACM Trans. Program. Lang. Syst. 16,* 3 (May), 428–455.

Briggs, P. and Torczon, L. 1993. An efficient representation for sparse sets. *ACM Lett. Program. Lang. Syst. 2,* 1-4 (March-December), 59–69.

Chaitin, G. J. 1982. Register allocation and spilling via graph coloring. *SIGPLAN Notices 17(6)*, 98–105. Proceeding of the ACM SIGPLAN '82 Symposium on Compiler Construction.

Chaitin, G. J., Auslander, M. A., Chandra, A. K., Cocke, J., Hopkins, M. E., and Markstein, P. W. 1981. Register allocation via coloring. *Comput. Lang. 6*, 47–57.

Chow, F. C. 1988. Minimizing register usage penalty at procedure calls. In *Proc. SIGPLAN '88 Conf. on Prog. Lang. Design and Implementation.* ACM Press, New York, 85–94.

CYTRON, R., FERRANTE, J., ROSEN, B. K., WEGMAN, M. N., AND ZADECK, F. K. 1991. Efficiently computing static single assignment form and the control dependence graph. *ACM Trans. Program. Lang. Syst. 13,* 4 (Oct.), 451–490.

GAREY, M. R. AND JOHNSON, D. S. 1979. *Computers and Intractability, A Guide to the Theory of NP-completeness.* Freeman. ISBN 0-7167-1044-7.

KEMPE, A. B. 1879. On the geographical problem of the four colors. *Am. J. Math. 2*, 193–200.

KRANZ, D., KELSEY, R., REES, J., HUDAK, P., PHILBIN, J., AND ADAMS, N. 1986. ORBIT: An optimizing compiler for Scheme. *SIGPLAN Notices (Proc. Sigplan '86 Symp. on Compiler Construction) 21,* 7 (July), 219–33.

LEROY, X. 1992. Unboxed objects and polymorphic typing. In *Nineteenth Annual ACM Symp. on Principles of Prog. Languages.* ACM Press, New York, 177–188.

SHAO, Z. AND APPEL, A. W. 1994. Space-efficient closure representations. In *Proc. 1994 ACM Conf. on Lisp and Functional Programming.* ACM Press, 150–161.

SHAO, Z. AND APPEL, A. W. 1995. A type-based compiler for Standard ML. In *Proc 1995 ACM Conf. on Programming Language Design and Implementation.* ACM Press, 116–129.

Received October 1995; accepted February 1996