Interprocedural Analysis Useless for Code Optimization

S. Richardson, M. Ganapathi

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Computer Systems Laboratory
Department of Electrical Engineering
Stanford University
Stanford, CA 94305

Abstract

The problem of tracking data flow across procedure boundaries has a long history of theoretical study by people who believed that such information would be useful for code optimization. Building upon previous work, we have implemented an algorithm for interprocedural data flow analysis. The algorithm produces three flow-insensitive summary sets: MOD, USE, and ALIASES. The utility of the resulting information was investigated using an optimizing Pascal compiler. Over a sampling of 27 benchmarks, we found that additional optimizations performed as a result of interprocedural summary information contributed almost nothing to program execution speed.

Key Words and Phrases: compiler, optimization, data flow analysis, interprocedural analysis, aliasing.
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1. Introduction

The presence of procedure calls forces most compilers to make conservative assumptions for code optimization. Usually, calls within blocks are treated as complex instructions that may affect the values of many variables. Global code optimizers perform data-flow analysis by handling procedure calls conservatively, since their effect is unknown. Consider the following example:

\[
\begin{align*}
\text{a} & := \text{b} + \text{c} \\
\text{call proc(d)} \\
\text{x} & := \text{b} + \text{c} \\
\text{y} & := \text{a} + \text{e}
\end{align*}
\]

If \text{proc(d)} kills the definition of \text{a}, then \text{a} := \text{b} + \text{c} does not reach \text{y} := \text{a} + \text{e}. In the absence of information about \text{proc}, it must be assumed conservatively that a procedure call is the definition of every variable visible at the call-site and all variable parameters.

Careful analysis of procedures can yield additional optimization opportunities that would otherwise have been wasted. Consider the following program skeleton.

```plaintext
program Ipatest(input, output);
var
gv: integer;
ba: array [1..1000] of integer;
i: integer;

procedure Sub;
begin
(* body of subroutine *)
end;

begin
  gv := 2;
  for i := 1 to 1000 do begin
    Sub;
    ba[gv*i] := 0; (* Clear ba if gv not set. *)
  end;
end.
```

If interprocedural analysis (ipa) can determine that the call to sub does not alter \text{gv}, the address calculation inside the loop can be significantly optimized. Such an interprocedural optimization can make the program run three times faster than when optimized without interprocedural analysis. Similarly, the presence of a call within a loop can prevent invariant code from being hoisted out of the loop.

Another example:

```plaintext
program test(input, output);
var
  i, j, k: integer;
  a: array [0..2000] of integer;

procedure check(var x: integer);
begin
  j := 2;
  for i := 0 to 1000 do begin
    x := 3; (* Does assignment alter \text{j}? *)
    a[i*j] := 0;
  end;
end;

begin
  check(k); (* body of program *)
end.
```

Inter-procedural analysis is necessary to determine that the parameter \text{x} is not aliased to \text{i} or \text{j} inside the subroutine "check". Once this has been determined, the constant expression "\text{x} := 3" can be hoisted out of the loop and the index expression \text{[i*j]} can be optimized. The optimized program becomes:
program test(input, output);
var
  i, j, k: integer;
  a: array [0..2000] of integer;

procedure check(var x: integer);
begin
  j := 2;
  x := 3;
  for tmp := 0 to 2000 step 2 do begin
    a[tmp] := 0;
  end;
  i := 1000;
end;

begin
  check(k);
  (* body of program *)
end.

A comprehensive treatment of interprocedural techniques including all facets of programming-language constructs and consequent quantitative analysis is still the subject of on-going research. Spillman analyzed the modification of variables considering almost all PL/I features, including recursion, reference parameters, procedure variables, label variables, pointers and exception handling [Spillman 71]. Allen used a very simple programming model, precluding procedure parameters and disallowing recursion but considering computation of modified-variables (MOD), used-variables (USE) and preserved-variables (PRESERVED) information [Allen 74]. Rosen considered a complicated but precise method to compute composite summary information [Rosen 76], yielding sharper information than those of earlier or later techniques. Lomet presented a simpler but less precise analogue of Rosen’s method [Lomet 77]. Barth extended Spillman’s technique, requiring multiple passes over the program, and computing algebraic relations across procedures and variables [Barth 77]. Banning used the call graph as a control flow graph; thus, standard global-data-flow analysis techniques were used in a one-pass algorithm to compute flow-insensitive summary information [Banning 79]. Weihl computed ranges of potential values for procedure variables, label variables and pointers independent of the program’s call graph or control-flow-graph [Weihl 80] and used Barth’s method to generate summary information. Myers showed that in the presence of aliasing, flow-sensitive summary problems are either IV-complete or co-NP complete [Myers 81]. Sharir and Pnueli treated the entire program as a single data-flow graph and solved problems on it [Sharir & Pnueli 81]. Jones and Muchnik considered a flexible approach to interprocedural flow analysis and programs with recursive data structures [Jones & Muchnik 82]. Cooper and Kennedy reformulated the algorithms of Banning and Myers resulting in a fast algorithm for interprocedural data flow analysis [Cooper & Kennedy 84]. They have concentrated on isolating and improving parts that are non-linear. Specifically, they isolated the tracking and closure effect of formal-parameter bindings, thus creating a more practical basis for the application of elimination techniques to Banning’s algorithm. Problems with this reformulation and corrections to fur these problems have been noted in the literature [Burke 84] [Carroll 87] [Cooper & Kennedy 87a]. Similarly, Burke and Cytron [Burke & Cytron 86] engineer the algorithm one step further to partition global-modification computation into local modification information and interprocedural binding patterns.

Research continues to focus on improving the efficiency of interprocedural techniques and analyzing the complexity of interprocedural side effect analysis [Cooper & Kennedy 87b] [Cooper & Kennedy 87c]. As we shall see later, our observation has been that efficiency, as defined by these techniques, is not the major problem. Rather, the potential benefit of the information must be questioned. In this paper we concentrate on the latter part of the problem. We take an existing algorithm and evaluate its utility in an optimizing compiler. The actual cost of implementation is contrasted with the potential gain obtained through program optimization. Thus, precision of interprocedural summary information and consequent improvement to the code can be determined.

The algorithm used in our own experiments computes flow-insensitive summary information similar to that computed by Banning panning 79] and Cooper and Kennedy [Cooper & Kennedy 84]. This information is
incorporated in an optimizing Pascal compiler [Chow 83] to attempt improvements in the execution efficiency of 27 benchmarks. These results are summarized in the concluding section.
2. Interprocedural Summary Information

The interprocedural analyzer scans through a source program just once and creates the program’s call-graph along with three flow-insensitive summary sets:

- **MOD(u)**, the set of variables global to procedure u that may be modified by a call to u.
- **USE(u)**, the set of variables global to procedure u that may be used during a call to u.
- **ALIASES(x)**, the set of variables which may be aliased to the variable x.

Banning used standard flow analysis techniques on the call-graph. Based on his work, we have derived the following equation for collecting inter-procedural MOD information:

\[
\text{MOD}(u) = \text{MOD}_0(u) \cup \bigcup_{e \in \text{CALL}(u,v)} \text{map} (\text{MOD}(v), \text{PTRS}(e))
\]

where

- \(\text{MOD}_0(u)\) is the set of non-local variables modified by procedure \(u\), without considering variables modified by procedure calls within \(u\).

- \(\text{PTRS}(e)\) is a list of ordered pairs representing the var parameters and their bindings at each call site \(e\). If procedure \(u\) makes a call to procedure \(v\) and passes the actual variables \(x, y,\) and \(z\) as formal parameters \(fp_1, fp_2,\) and \(fp_3\) at call site \(c\), then

\[
\text{PTRS}(c) = \{(fp_1, x), (fp_2, y), (fp_3, z)\}.
\]

\(\text{map}(\text{MOD}(v), \text{PTRS}(e))\) searches \(\text{MOD}(v)\) for any elements which are also formal reference parameters of procedure \(v\). It then replaces these elements with the corresponding actual parameter as given by \(\text{PTRS}(e)\) for the call site \(e\). As an example, if

\[
\text{MOD}(v) = \{a, b, c, fp_1\} \text{ and } \text{PTRS}(e) = \{(fp_1, x), (fp_2, y), (fp_3, z)\},
\]

then

\[
\text{map}(\text{MOD}(v), \text{PTRS}(e)) = \{(a, b, c, x)\}
\]

We implement this equation using the following algorithm:

```plaintext
(* Initialize *)
foreach procedure u do begin
    MOD(u) := MOD_0(u);
    CALLS(u) := CALLS_0(u);
end;
newsets := true;

(* Calculate MOD set *)
while (newsets) do begin
    newsets := false;
    foreach procedure u do begin
        foreach callsite e = (u, v) E CALLS(u) do begin
            MOD'(v) = map (MOD(v), PTRS(e));
            if (MOD(u) \cup MOD'(v) ≠ \O) then begin
                MOD(u) := MOD(u) \cup MOD'(v);
                CALLS(u) := CALLS(u) \cup CALLS(v);
                newsets := true;
            end;
        end;
    end;
end;
```

The algorithm for collecting USE information is strictly analogous to the algorithm for collecting MOD information.

In program optimization, it is helpful to know variables that may potentially be aliased to other variables. Thus,
for each variable $x$ in a program, we calculate $\text{ALIASES}(x)$, the set of possible aliases for variable $x$. $\text{ALIASES}(x)$ is formed by taking the transitive closure of a simpler set $\text{ALIASES}_0(x)$, the set of actual parameters that are bound to formal parameter $x$.

\[
\begin{align*}
\text{(* Initialize *)} \\
\text{foreach procedure } u \text{ do begin} \\
\text{foreach varparameter } x_u \text{ do begin} \\
\quad \text{ALIASES}(x_u) := \text{ALIASES}_0(x_u); \\
\text{end;} \\
\text{end;} \\
\text{(* Calculate ALIAS set *)} \\
\text{change} := \text{true;} \\
\text{while (change) do begin} \\
\quad \text{change} := \text{false;} \\
\text{foreach procedure } u \text{ do begin} \\
\quad \text{foreach varparameter } x_u \text{ do begin} \\
\quadquad \text{foreach actualparameter } ap=\text{ALIASES}(x_u) \text{ do begin} \\
\quadquadquad \text{if } \text{ALIASES}(x_u) \cap \text{ALIASES}(ap) \neq \emptyset \text{ then begin} \\
\quadquadquadquad \text{change} := \text{true;} \\
\quadquadquadquad \text{ALIASES}(x_u) := \text{ALIASES}(x_u) \cup \text{ALIASES}(ap); \\
\quadquadquad \text{end; (* if *)} \\
\quadquad \text{end (* foreach *)} \\
\quad \text{end (* foreach *)} \\
\text{end (* while *)}
\end{align*}
\]
3. Influencing Global Optimization

An existing global optimizer (UOPT)[Chow83] was used to explore potential benefits from the computed interprocedural summary information. UOPT has been used in the Stanford U-Code compiler system since 1983 and has proven effective over a wide range of programs. It operates as an optional extra pass performed on the intermediate code output from the compiler front end, and its output in turn is used by the compiler back-end to generate machine code for a given target machine. To improve execution efficiency, the following global optimizations are performed:

1. Stack height reduction in expression evaluation.
2. Constant propagation.
3. Constant expression evaluation at compile time.
4. Address collapsing in array expressions.
5. Dead code elimination.
6. Copy propagation.
7. Common subexpression elimination.
8. Loop-invariant expression optimization.
10. Loop induction-expression optimization (strength reduction).
11. Linear function test replacement and induction variable elimination.
12. Redundant store elimination.
13. Dead variable elimination.
14. Partial redundancy suppression by forward code motion.
15. Global register allocation and assignment.

To a large extent, these optimizations depend upon the use of data flow information; the accuracy of which can theoretically be improved with the use of interprocedural summary information.

The optimizer makes the following assumptions concerning data flow:

1. Direct access of a memory location affects only the memory location accessed
2. Indirect access through a pointer to a known memory location affects only the known location.
3. Indirect access through a pointer to an unknown memory location affects all non-local variables.
4. Access of a var parameter affects access to all non-local variables. For example, a store to a var parameter kills all globals and all var parameters.
5. Access of a var parameter is affected by access to all non-local variables. For example, a store to a global kills all var parameters.
6. A procedure call affects all variables in the scope of the called procedure.

Assumptions (1) and (2) are precise and therefore cannot be improved.

Assumption (3) is a worst-case assumption that can be improved by tracking pointer dereferences. The algorithm presented here does not address the problem of tracking pointers, although in the future, pointers can be handled in a way similar to ALIASES computation, for reference parameters. The interprocedural analyzer can collect all the address ranges throughout the program whose addresses have been taken via a load-address instruction and stored somewhere or passed as a parameter. When UOPT sees an indirect store, it need kill only these addresses instead of
Assumptions (4) and (5) are worst-case assumptions that improve with the addition of the ALIASES summary set. Access of var parameter \( v_p \) affects only the aliases of \( v_p \) in the set \( \text{ALIASES}(v_p) \).

Most importantly, the use of MOD and USE sets allow us to remove the worst-case restriction in assumption (6). Rather than assuming that a procedure call affects all variables in unknown ways, we can precisely convey that a call to procedure P modifies only those variables in the set \( \text{MOD}(P) \) and uses only those variables in \( \text{USE}(P) \).

### 3.1. Optimization with MOD Information

MOD sets allow the global optimizer to determine whether or not a given variable is killed (modified) by a given procedure call. This information may be used in turn to calculate flow information and liveness information for various types of code optimization, including:

- constant folding/constant propagation
- copy propagation
- strength reduction
- induction variable elimination
- common subexpression elimination
- redundant store elimination
- code motion

As an example, consider the following code from “pwhets”, a Pascal version of the Whetstone benchmark (the various benchmarks used in this paper are described in Appendix I):

```pascal
for j = 1 to n do begin
  n1 = 0;
  n2 = L2 * i;
  n3 = L4 * i;
  Sub(n1, n2, n3);
end;
```

```pascal
for j = 1 to n do begin
  n1 = 0;
  n2 = L2 * i;
  n3 = L4 * i;
  Sub(n1, n2, n3);
end;
```

- **a. UNOPTIMIZED**
- **b. UOPT, no IPA (no change)**
- **c. UOPT + IPA**

**Figure 3-1:** Effect of MOD Sets on Optimization

The variables i, n1, n2, and n3 are global to procedure Sub. Thus, without the help of MOD sets, the global optimizer can do nothing to improve the running speed of the loop (Figure 3-1b). Because the variables are not in fact modified by the call to subroutine “Sub” (\( \text{MOD}(\text{Sub}) = \emptyset \)), the use of MOD information allows us to move all three assignments out of the loop (Figure 3-1c).

Another bit of pwhets code is shown in Figure 3-2.

```pascal
l = 0.499975;
t2 = 0.500025;
Sub();
e1 = expr1 * t;
e4 = expr4 / t2;
```

- **a. UOPT, no IPA**
- **b. UOPT + IPA**

**Figure 3-2:** Effect of MOD Sets on Optimization
The global optimizer was unable to do anything to the original code because of uncertainty as to the fates of global variables \( t \) and \( t_2 \) during the call to Sub. After using interprocedural MOD information to determine that procedure Sub does not modify either of the global variables \( t \) or \( t_2 \) (\( \text{MOD(Sub)} = \emptyset \)), the code was optimized as shown in Figure 3-2b.

Finally, consider the program given below as Figure 3-3a. Because variables \( g_v \) and \( i \) are global to subroutine "Subl," the global optimizer UOPT was initially unable to optimize the loop in any way. Once the MOD sets were used to determine that neither \( g_v \) nor \( i \) are modified by "Subl" (\( \text{MOD(Subl)} = \emptyset \)), the optimizer was able to eliminate the variable "\( g_v \)" and the repetitive array index calculation "\( \text{ba}[g_v*i] \)," as shown in Figure 3-3b.

\[
\begin{align*}
g_v &= 2; \\
\text{for } i &= 1 \text{ to } 1000 \text{ do begin} \\
& \quad \quad \text{begin} \\
& \quad \quad \quad \text{Subl();} \\
& \quad \quad \quad \text{ba[gv*i]} = 13; \\
& \quad \quad \quad \text{end;}
\end{align*}
\]

\[
\text{a. UOPT, no IPA} \quad \text{b. UOPT + IPA}
\]

Figure 3-3: Effect of MOD Sets on Optimization

3.2. Optimization with USE Information

The interprocedural summary set USE may be used by UOPT to determine whether or not a given variable is used by a given procedure call. As seen previously with MOD information, USE information can be used to calculate flow information and liveness for use with various types of code optimization.

The example given below illustrates how USE information can be used to perform register allocation in the presence of procedure calls.

The cyk benchmark contains the following code before optimization (Figure 3-4).

\[
\begin{align*}
\text{for } i &= 1 \text{ to } n \text{ do begin} \\
& \quad \quad \quad \text{begin} \\
& \quad \quad \quad \quad \text{for } j = 1 \text{ to } n \text{ do begin} \\
& \quad \quad \quad \quad \quad \quad \quad \text{for } k = 1 \text{ to } n \text{ do begin} \\
& \quad \quad \quad \quad \quad \quad \quad \quad \text{P2[i, j, k]} := \text{true;}
\end{align*}
\]

\[
\text{end;}
\]

\[
\text{end;}
\]

\[
\text{end;}
\]

\[
\text{for } i &= 1 \text{ to } L \text{ do } x[i] := 1; \\
\text{cyksub}(x, \text{P2});
\]

Figure 3-4: Unoptimized cyk Code

The optimizer allocates global variables \( i, j, \) and \( k \) to the registers \( R_0, R_1, \) and \( R_2 \) respectively. Without interprocedural analysis to tell it about use patterns within the procedure cyksub, it produces the code in Figure 3-5.

\[
\begin{align*}
\text{for } R_0 &= 1 \text{ to } n \text{ do begin} \\
& \quad \quad \quad \quad \text{begin} \\
& \quad \quad \quad \quad \quad \quad \quad \text{for } R_1 = 1 \text{ to } n \text{ do begin} \\
& \quad \quad \quad \quad \quad \quad \quad \quad \quad \text{for } R_2 = 1 \text{ to } n \text{ do begin} \\
& \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \text{P2[R_0, R_1, R_2]} := \text{true;}
\end{align*}
\]

\[
\text{end;}
\]

\[
\text{k := R_2;}
\]

\[
\text{end;}
\]

\[
\text{j := R_1;}
\]

\[
\text{end;}
\]

\[
\text{for } R_0 &= 1 \text{ to } L \text{ do } x[R_0] := 1; \\
\text{i := R_0;}
\]

\[
\text{cyksub}(x, \text{P2});
\]

Figure 3-5: cyk Code Optimized without the Use of Interprocedural Information
By referring to the USE sets, the optimizer can determine that i, j, and k are not used inside procedure cyksub (USE(cyksub) = $\emptyset$), obviating the need for the three updates marked by "(**)". The resulting code is as shown in Figure 3-6 below.

```plaintext
for R_s := 1 to n do begin
    for R_i := 1 to n do begin
        P[R_i, R_s, R_k] := true;
    end;
end;
for R_s := 1 to L do x[R_s] := 1;
cyksub(x, P2);
```

Figure 3-6: cyk Code Optimized Using Interprocedural USE Sets

The savings to the algorithm from this optimization is easily calculated. The expression inside the loop is calculated exactly $n^3$ times. The stores occur once for each of the outer loops, for a total of $n^2 + 1$ stores. For large n, the savings translates to a speedup of

$$\frac{n^3}{(n^3 - n^2 - n)}$$

USE information can also be used to perform linear test replacement, as shown by Figure 3-7. Two other procedures are within the scope of variable c. Without interprocedural analysis, the global optimizer UOPT was unable to optimize the given code. With the addition of USE sets, it became known that neither of the other two procedures used variable c, and the result was code optimized as shown by Figure 3-7b.

Figure 3-8a shows more unoptimized code from the pwhets benchmark.

```plaintext
diff = 17;
for i = 1 to 1000 do begin
    diff = P(x, i) / i;
    this = diff;
end;
```

```plaintext
a. UNOPTIMIZED
```

When optimized without the use of interprocedural summary information, the global optimizer allocates the variable “diff” to register $R_0$, as shown in Figure 3-8b. When the global optimizer is allowed to use interprocedural summary information, it finds that “diff” does not appear in the set USE(P), i.e. “diff” is not used by procedure P. Thus, the optimizer was able to remove the update of diff at the beginning of the loop, producing the code shown in Figure 3-8c.

```plaintext
diff = 17;
for i = 1 to 1000 do begin
    diff = P(x, i) / i;
    this = diff;
end;
```

```plaintext
b. UOPT, no IPA
```

```plaintext
diff = 17;
for i = 1 to 1000 do begin
    diff = P(x, i) / i;
    this = diff;
end;
```

```plaintext
c. UOPT + IPA
```
3.3. Optimization with ALIAS Information

ALIAS sets are used to determine whether a given variable has potential aliases, such that unknown side effects may occur as a result of storing to the variable in question.

Note the following example of how ALIAS sets were used to improve register allocation. In the benchmark “bigfm” we find the code shown in Figure 3-9.

```
procedure Onestep(var bestgain: pinrange);

procedure Findbest(...);

procedure initchain(cell: cellrange; gain: pinrange);
begin
    new(bestchain);
    bestchain^.next = nil;
    bestchain^.number = cell;
    lastlink = bestchain;
    bestgain = gain;
    bestlink = bestchain;
end;

begin ... end;
begin ... end;
```

**Figure 3-9:** Unoptimized Source Code from the “bigfm” Benchmark

Uncertainty as to whether var parameter “bestgain” and global variable “bestchain” are aliased initially prevented the optimizer from allocating “bestchain” to a register. Once ALIAS information was referenced, the optimizer yielded the code shown in Figure 3-10.

```
procedure Onestep(var bestgain: pinrange);

procedure Findbest(...);

procedure initchain(cell: cellrange; gain: pinrange);
begin
    new(R_0);
    R_0^.next = nil;
    R_0^.number = cell;
    lastlink = R_0;
    bestgain = gain;
    bestlink = R_0;
end;

begin ... end;
begin ... end;
```

**Figure 3-10:** Optimized “bigfm” Code, using Interprocedural Information

UOPT was unable to optimize the code given in Figure 3-11 without the help of interprocedural ALIAS sets. However, once the ALIAS sets were calculated and utilized, optimized code was produced as shown in Figure 3-12. The alias set for x was found to be: ALIASES(x) = {j}.

Because x is not aliased to i or a, the computation x=3 was moved out of the loop.

Because x is not aliased to i, i was replaced by a register.

Because x is aliased to j through at least one path, no assumptions were made as to the value of j inside the loop.

ALIAS information allowed the global optimizer to perform linear test replacement on the program shown in Figure 3-13. Optimization without interprocedural analysis is unable to do anything to the program because of
program test(input, output);
var
  i, j, k: integer;
  a: array [0..2000] of integer;
procedure init(var x: integer);
j = 2;
begin
  for i = 0 to 1000 do begin
    x = 3;
a[i*j] = 0;
  end;
end;
begin
  init(j);
end.

Figure 3-11: Benchmark, Unoptimizable without Interprocedural Information

program test(input, output);
var
  i, j, k: integer;
  a: array [0..2000] of integer;
procedure init(var x: integer);
j = 2;
x = 3;
begin
  for i := 0 to 1000 do begin
    a[i*j] = 0;
  end;
end;
begin
  init(j);
end.

Figure 3-12: Optimized Benchmark, Using ALIAS Sets

program test(input, output);
var
  i, j, k: integer;
  a: array [0..2000] of integer;
procedure init(var x: integer);
j = 2;
begin
  for i = 0 to 1000 do begin
    a[i*j] = 0;
  end;
end;
begin
  init(k);
end.

Figure 3-13: Benchmark, Unoptimizable without Interprocedural Information

possible aliasing patterns between the var parameter x and the global variables i, j, k, and the global array a. Optimization with the benefit of inter-procedural analysis thrown in yields the code shown in Figure 3-14. Because j is not aliased to var parameter x (ALIASES(x) = {k}), it was recognized as a loop-invariant constant, and the array reference inside the loop was linearized.

As a final example of where ALIAS information can help optimize programs, Figure 3-15 presents procedure "P3" from the pwhets benchmark. It is obvious that the local variables x, y, and tmp may be allocated to registers. Interprocedural analysis, specifically the use of ALIAS sets, is required to show that the var parameter z is not aliased to the non-local t before t can be allocated to a register. Using interprocedural analysis, the optimizer was able to produce the version of P3 shown in Figure 3-16.
program test(input, output);
var
  i, j, k: integer;
  a: array [0..2000] of integer;
  procedure init(var x: integer);
  begin
    R0 := a[0];
    for i := 0 to 1000 do begin
      *R0 := 0;
      R0 := R0 + 2 * INT_SIZE;
    end;
  end;
begin
  init(k);
end.

Figure 3-14: Use of ALIAS Information Allows Linear Test Replacement

procedure P3(x, y: real; var z: real);
var tmp: real;
begin
  tmp = (x + y) * t;
  z = ((tmp + y) * t + tmp) / t2;
end;

Figure 3-15: Procedure P3, Unoptimized

procedure P3(x, y: real; var z: real);
var tmp: real;
begin
  R0 = x;
  R1 = y;
  R2 = t;
  R3 = (R0 + R1) * R2;
  R4 = cz;
  R5 = t2;
  *R4 := [ (R3 + R1) * R2 + R3 ] / R5;
end;

Figure 3-16: Procedure P3, Optimized with Use of ALIAS Sets
4. Experimental Observations

The interprocedural analyzer was implemented using 9300 lines of Pascal source code. Interprocedural summary information was processed at a rate of approximately one second of VAX780 cpu time per 10 lines of Pascal source, adding about 15% to the total compile time. The global optimizer ran 10% to 20% slower when utilizing interprocedural information; most of this time was spent reading a given benchmark’s associated interprocedural summary file for a given benchmark. This time could be substantially improved by storing the summary information in a more optimal format.

The benchmarks

27 Pascal benchmarks were used in evaluating the overall effect of interprocedural analysis on program speedup. Figure 4-1 lists the names of these benchmarks, along with some statistics:

| lines | The number of lines of source code in the benchmark. |
| proc | The number of procedures defined statically in each program. |
| lifetime | The percentage of loads and stores that occur within the leaf procedures of each program. Procedures that make only system calls are counted as leaf procedures. |
| intcall | Within a given procedure P, MOD and USE information affects only those operations involving variables that are within the scope of one or more procedures called by P. By counting the number of accesses to such variables, we get an idea of the possible impact of MOD and USE information on the optimization of the program. This number, represented as a percentage of all memory accesses, is intcall. The calculation of intcall is discussed further below. |
| intalias | ALIAS information is important only within procedures that access var parameters. Interference only occurs between either a var parameter and a global or one var parameter and another var parameter. The percentage of memory accesses that are susceptible to such interference is calculated as intalias. |

The figure of merit for procedure call interference intcall is defined as the ratio of memory accesses susceptible to interference by procedure calls to all memory accesses. If we believe that the number of cycles saved by global optimization is proportional to the number of loads and stores eliminated, then intcall gives us an upper bound for the amount of speedup to be obtained through the use of MOD and USE information.

Within a given procedure P, the number of memory accesses susceptible to interference by procedure calls is intcall(P). For a leaf procedure LF, intcall(LF) is zero, i.e. no memory references interfere with procedure calls. For a procedure GE that calls only itself and/or up-level procedures, intcall(GE) is equal to the number of direct accesses to global variables from within GE. For a procedure LT making at least one call to a procedure within its static scope, intcall(LT) is equal to the number of all direct memory accesses, local or global, made by LT.

As shown in the table, the average benchmark had 1190 lines of source code and 30 procedures. Nearly 50% of all memory accesses occurred in leaf procedures. 15% of all memory accesses had potential interference with a procedure call. 1% of all memory accesses could potentially be aliased to other variables via the mechanism of pass-by-reference parameter binding.

Note that the metrics intcall and intalias are based on worst-case estimates of data flow patterns within a procedure. Were actual data flow taken into account, these numbers would become strictly smaller. As an example of where our worst-case estimate differs from actual numbers, consider the bubble-sort benchmark bubble.p. This program begins with a call to an initialization procedure Initarr. In the next basic block, the global variable i is defined, after which it is accessed 750,000 times within a loop. In this case, intcall counts 750,000 possible interferences whereas,

---

1. Similarly, intalias may give us an upper bound for the amount of speedup to be obtained through the use of ALIAS information.

2. Indirect accesses through pointers are not affected by interprocedural analysis.
<table>
<thead>
<tr>
<th>filename</th>
<th>lines</th>
<th>procs</th>
<th>ltime</th>
<th>int_call</th>
<th>int_alias</th>
</tr>
</thead>
<tbody>
<tr>
<td>ack</td>
<td>15</td>
<td>2</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>uniforum</td>
<td>18</td>
<td>1</td>
<td>100%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>fib</td>
<td>19</td>
<td>2</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>loop1 la</td>
<td>22</td>
<td>1</td>
<td>100%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>sieve</td>
<td>33</td>
<td>1</td>
<td>100%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>cyk</td>
<td>44</td>
<td>2</td>
<td>100%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>intmm</td>
<td>76</td>
<td>6</td>
<td>99%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>queen</td>
<td>64</td>
<td>2</td>
<td>0%</td>
<td>1%</td>
<td>0%</td>
</tr>
<tr>
<td>bubble</td>
<td>84</td>
<td>5</td>
<td>0%</td>
<td>68%</td>
<td>0%</td>
</tr>
<tr>
<td>perm</td>
<td>86</td>
<td>7</td>
<td>41%</td>
<td>12%</td>
<td>0%</td>
</tr>
<tr>
<td>strings</td>
<td>107</td>
<td>6</td>
<td>56%</td>
<td>35%</td>
<td>0%</td>
</tr>
<tr>
<td>place</td>
<td>119</td>
<td>9</td>
<td>97%</td>
<td>2%</td>
<td>0%</td>
</tr>
<tr>
<td>tree</td>
<td>122</td>
<td>8</td>
<td>16%</td>
<td>52%</td>
<td>0%</td>
</tr>
<tr>
<td>simple</td>
<td>172</td>
<td>5</td>
<td>63%</td>
<td>22%</td>
<td>0%</td>
</tr>
<tr>
<td>puzzle</td>
<td>155</td>
<td>5</td>
<td>95%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>dlhrystone</td>
<td>251</td>
<td>12</td>
<td>46%</td>
<td>32%</td>
<td>4%</td>
</tr>
<tr>
<td>pwhets</td>
<td>350</td>
<td>10</td>
<td>64%</td>
<td>19%</td>
<td>3%</td>
</tr>
<tr>
<td>tlb</td>
<td>354</td>
<td>14</td>
<td>23%</td>
<td>59%</td>
<td>0%</td>
</tr>
<tr>
<td>newtlb</td>
<td>355</td>
<td>14</td>
<td>14%</td>
<td>27%</td>
<td>0%</td>
</tr>
<tr>
<td>bigfm</td>
<td>541</td>
<td>18</td>
<td>33%</td>
<td>11%</td>
<td>0%</td>
</tr>
<tr>
<td>ccac</td>
<td>799</td>
<td>27</td>
<td>8%</td>
<td>18%</td>
<td>3%</td>
</tr>
<tr>
<td>bench</td>
<td>941</td>
<td>48</td>
<td>75%</td>
<td>3%</td>
<td>0%</td>
</tr>
<tr>
<td>dfn</td>
<td>1585</td>
<td>37</td>
<td>44%</td>
<td>1%</td>
<td>8%</td>
</tr>
<tr>
<td>hopt</td>
<td>2197</td>
<td>92</td>
<td>66%</td>
<td>12%</td>
<td>11%</td>
</tr>
<tr>
<td>simu</td>
<td>3458</td>
<td>101</td>
<td>11%</td>
<td>13%</td>
<td>5%</td>
</tr>
<tr>
<td>macro</td>
<td>7484</td>
<td>179</td>
<td>33%</td>
<td>26%</td>
<td>10%</td>
</tr>
<tr>
<td>upasmpis</td>
<td>13768</td>
<td>235</td>
<td>5%</td>
<td>39%</td>
<td>16%</td>
</tr>
<tr>
<td>(average)</td>
<td>1230</td>
<td>31</td>
<td>47%</td>
<td>15%</td>
<td>1%</td>
</tr>
</tbody>
</table>

**Figure 4-1:** Benchmark Statistics

Once we actually do the data flow analysis, we find that there is no interference between the procedure call and i. Simple inspection of the statistical data for bubble.p shows that the actual number of interferences is almost nil, even though our algorithm reports a possible 68% interferences between variables and procedure calls.

Each benchmark was run four times, with varying degrees of interprocedural analysis taken into account. The results are reported in figure 4-2 under four columns labeled as shown below:

- **uopt, no ipa**: The program was compiled and optimized, but no inter-procedural summary information was used. Worst-case assumptions were made concerning procedure calls and aliasing. The program speedup is reported as compared to the running time of an unoptimized program. For example, 1.09 means 9% faster.

- **uopt + alias**: The program was compiled and optimized using ALIAS summary information. Program speedup is reported versus the running time of an unoptimized program. In parentheses is shown the incremental difference between the running time of the program as compiled and optimized without the use of any interprocedural summary information (plain vanilla optimization) versus the running time of the program as compiled and optimized with ALIAS information added (i.e. uopt, no ipa versus uopt + alias). A difference of 0% means that the addition of ALIAS information caused the running time of the program to improve by less than 1%.

- **uopt + mod/use**: The program was compiled and optimized using MOD and USE summary information. Program speedup is reported versus the running time of an unoptimized program. In parentheses is shown the difference between the plain vanilla optimization for this program versus the running time of the program as compiled with MOD and USE information (i.e. uopt, no ipa versus uopt + mod/use).

- **uopt + both**: The program was compiled and optimized using all available interprocedural summary...
Of a suite of 27 benchmarks, only two showed an improvement greater than 2%. The failure of these benchmarks to produce satisfactory results leads to the following conclusions.

- The call graphs for these benchmarks are not complex. Much of a program’s running time is spent either in leaf procedures or in areas where procedure calls do not interfere significantly with data flow patterns.

- Aliasing patterns in these benchmarks are not complex.

Our work has been limited to the domain of Pascal programs running on a sequential machine. However, our results seem to concur with those of Allen, Callahan, and Kennedy [Allen et al 86 861, who report a similar lack of improvement for FORTRAN programs running in the context of a vectorizing compiler.

<table>
<thead>
<tr>
<th>filename</th>
<th>uopt, no ipa</th>
<th>uopt + alias</th>
<th>uopt + mod/use</th>
<th>uopt + both</th>
</tr>
</thead>
<tbody>
<tr>
<td>ack</td>
<td>1.11</td>
<td>1.11 (0%)</td>
<td>1.11 (0%)</td>
<td>1.11 (0%)</td>
</tr>
<tr>
<td>bench</td>
<td>2.07</td>
<td>2.07 (0%)</td>
<td>2.07 (0%)</td>
<td>2.07 (0%)</td>
</tr>
<tr>
<td>bigfm</td>
<td>1.53</td>
<td>1.54 (0%)</td>
<td>1.53 (0%)</td>
<td>1.53 (0%)</td>
</tr>
<tr>
<td>bubble</td>
<td>3.00</td>
<td>3.00 (0%)</td>
<td>3.00 (0%)</td>
<td>3.00 (0%)</td>
</tr>
<tr>
<td>ccal</td>
<td>1.16</td>
<td>1.16 (0%)</td>
<td>1.17 (0%)</td>
<td>1.17 (0%)</td>
</tr>
<tr>
<td>cyk</td>
<td>1.60</td>
<td>1.60 (0%)</td>
<td>1.60 (0%)</td>
<td>1.60 (0%)</td>
</tr>
<tr>
<td>dhrystone</td>
<td>1.17</td>
<td>1.17 (0%)</td>
<td>1.18 (0%)</td>
<td>1.18 (0%)</td>
</tr>
<tr>
<td>dnf</td>
<td>1.28</td>
<td>1.28 (0%)</td>
<td>1.28 (0%)</td>
<td>1.28 (0%)</td>
</tr>
<tr>
<td>fib</td>
<td>1.09</td>
<td>1.09 (0%)</td>
<td>1.09 (0%)</td>
<td>1.09 (0%)</td>
</tr>
<tr>
<td>hopt</td>
<td>1.06</td>
<td>1.06 (0%)</td>
<td>1.06 (0%)</td>
<td>1.06 (0%)</td>
</tr>
<tr>
<td>intmm</td>
<td>2.07</td>
<td>2.07 (0%)</td>
<td>2.07 (0%)</td>
<td>2.07 (0%)</td>
</tr>
<tr>
<td>looplla</td>
<td>2.91</td>
<td>2.91 (0%)</td>
<td>2.91 (0%)</td>
<td>2.91 (0%)</td>
</tr>
<tr>
<td>macro</td>
<td>1.15</td>
<td>1.15 (0%)</td>
<td>1.15 (0%)</td>
<td>1.15 (0%)</td>
</tr>
<tr>
<td>newtlb</td>
<td>1.19</td>
<td>1.19 (0%)</td>
<td>1.27 (7%)</td>
<td>1.27 (7%)</td>
</tr>
<tr>
<td>perm</td>
<td>1.27</td>
<td>1.27 (0%)</td>
<td>1.27 (0%)</td>
<td>1.27 (0%)</td>
</tr>
<tr>
<td>place</td>
<td>2.74</td>
<td>2.74 (0%)</td>
<td>2.74 (0%)</td>
<td>2.74 (0%)</td>
</tr>
<tr>
<td>puzzle</td>
<td>2.45</td>
<td>2.45 (0%)</td>
<td>2.45 (0%)</td>
<td>2.45 (0%)</td>
</tr>
<tr>
<td>pwhets</td>
<td>1.09</td>
<td>1.09 (0%)</td>
<td>1.09 (0%)</td>
<td>1.09 (0%)</td>
</tr>
<tr>
<td>queen</td>
<td>1.55</td>
<td>1.55 (0%)</td>
<td>1.55 (0%)</td>
<td>1.55 (0%)</td>
</tr>
<tr>
<td>sieve</td>
<td>2.19</td>
<td>2.19 (0%)</td>
<td>2.19 (0%)</td>
<td>2.19 (0%)</td>
</tr>
<tr>
<td>simple</td>
<td>1.48</td>
<td>1.48 (0%)</td>
<td>1.48 (0%)</td>
<td>1.48 (0%)</td>
</tr>
<tr>
<td>simu</td>
<td>1.22</td>
<td>1.22 (0%)</td>
<td>1.22 (0%)</td>
<td>1.22 (0%)</td>
</tr>
<tr>
<td>strings</td>
<td>1.53</td>
<td>1.53 (0%)</td>
<td>1.55 (1%)</td>
<td>1.55 (1%)</td>
</tr>
<tr>
<td>tlb</td>
<td>1.07</td>
<td>1.07 (0%)</td>
<td>1.19 (12%)</td>
<td>1.19 (12%)</td>
</tr>
<tr>
<td>tree</td>
<td>1.20</td>
<td>1.20 (0%)</td>
<td>1.25 (4%)</td>
<td>1.25 (4%)</td>
</tr>
<tr>
<td>uniforum</td>
<td>1.31</td>
<td>1.31 (0%)</td>
<td>1.31 (0%)</td>
<td>1.31 (0%)</td>
</tr>
<tr>
<td>upasmips</td>
<td>1.04</td>
<td>1.04 (0%)</td>
<td>1.04 (0%)</td>
<td>1.04 (0%)</td>
</tr>
</tbody>
</table>

Figure 4-2: Benchmark Improvement
5. Conclusions

An interprocedural analyzer has been implemented and integrated into an existing Pascal compiler [Chow 83]. The efficiency of the algorithm used to perform inter-procedural analysis was not considered an issue, as our concern was to explore the result of using such analysis in an optimizing compiler. Our observations reveal that in an optimizing Pascal compiler, interprocedural summary information can produce interesting and tangible optimizations. Unfortunately, these optimizations do not happen in the frequently executed parts of a program. Thus, due to the characteristics of Pascal programs, inter-procedural information is unnecessary for code optimization.

**ALIAS** information, which is the most difficult to compute algorithmically, turns out to be the least useful. Our data show that only about 1% of the loads and stores in a given program are susceptible to being potentially aliased to a *var* parameter, and that the actual speedup gained by making such relationships explicit is almost nil.

MOD and USE information fares little better. On average, we find that 15% of loads and stores potentially interfere with procedure calls within the program. The actual speedup gained after using MOD and USE information is about 1%. The difference comes from the fact that worst-case assumptions are either correct or superfluous most of the time. For instance, if a given variable is defined immediately after a procedure call, the procedure call’s possible use of the variable is superfluous. Similarly, if inter-procedural information tells us that a given variable is used by a given procedure call, this merely affirms the fact that our worst case assumption (all procedure calls affect all variables) is correct in this particular case.

Altogether, these statistics effectively defuse potential optimization opportunities that would otherwise have arisen due to lack of interprocedural summary information. Thus, the effective improvement in the results of optimizing transformations does not justify the expense of determining side-effects and aliases. It seems that a simple static scan could prove a reasonably practical alternative for inter-procedural analysis. For example, since ‘Must’ items are not needed in global code-optimization, other value-items can be easily derived by a global optimizer.

Although our observations have been limited to the domain of Pascal programs, it is interesting to note that others [Allen et al 86] have reached similar conclusions in the domain of vectorizing FORTRAN programs. They claim that USE and MOD sets increase the accuracy of information, but in the final analysis they do not help programs run faster. They also claim that alias analysis does not help much because aliasing is usually very rare. In addition, they note that interprocedural constant propagation does not produce significant run-time improvements. Similarly, Burke [Burke 84] notes that the potential benefits of interprocedural summary information are not significant when compiling for sequential machines. Our results concur with these observations and they tend to verify that potential benefits of inter-procedural optimization are indeed small for Pascal programs.
Appendix I
Benchmark Descriptions

ack Ackerman's function.

bench Combination of the 10 Stanford benchmarks: bubble, dnf, perm, queen, tower, quick, tree, mm, puzzle, and fft.

bigfm An implementation of the Fiduccia-Mattheyses algorithm as described in 19th DA, pp 175-181. This algorithm reads a netlist of a hyper-graph from standard input and produces a partition of that graph into two (roughly) equal sized sections, written to standard output. The algorithm adapts the Kemighan-Lin algorithm for graph partition by adding data structures to speed the calculation of the biggest gain, and the updating of gains of neighbors for each move.

bubble Bubble sort.

cal Interactive desk calculator, written by Warren Cory of Stanford University.


dhrystone An integer version of whetstone.

dnf A normalizer from arbitrary boolean expressions to Disjunctive Normal Form.

fib A heavily recursive algorithm for printing out the Fibonacci sequence.

hopx Optimizer for intermediate code, written by Edwin Hou of Stanford University.

intmm Multiply two integer matrices.

looplla Sums the elements of two large arrays in a unique way.

macro Macro expansion preprocessor for the SCALD computer-aided &sign system developed by T. M. McWilliams and L. C. Widdoes of Stanford University. It is described in Stanford University Technical Report 152, Digital Systems Laboratory, March 1978.

newtlb TLB and cache simulator. Same as “tlb.p” except with a different set of constants (i.e. different sizes for the cache and TLB).

perm A permutation program written by Denny Brown to illustrate recursion.

place Evaluate and find placements assuming cheap line placement.

puzzle An undocumented compute-bound program from Forest Baskett.

pwhets A Pascal version of the whetstone program.

queen A heavily recursive solution to the 8 queens problem.


simu Simulation of an Operating System.

strings A hash table for character strings.

tlb TLB and cache simulator.

tree sorts an array.

uniforum Multiplication of two integer arrays.
Appendix II
Bibliography Notes


[Allen 74] Allen presents an algorithm for finding (1) “uses of data items in a procedure which can be affected by outside definitions,” and (2) “data items which may be changed when a procedure is referenced.” The algorithm is restricted to non-recursive procedures connected by a well-defined control flow graph. These restrictions are removed in a later paper [Allen & Schwartz 74]. The algorithm is implemented in IBM’s Experimental Compiler System (ECS).


[Allen & Schwartz 74] An extension of a previously-presented inter-procedural data flow algorithm [Allen 74] which uses “overestimates” and “worst-case assumptions” to allow for recursive procedures and a control flow graph that is not well defined.

[Allen et al 80] A comprehensive discussion of the Experimental Compiler System (ECS), representing “a new compiler construction methodology that uses a compiler base which can be augmented to create a compiler for any one of a wide class of source languages.” The system calculates interprocedural summary information and incorporates procedure inlining and interprocedural constant propagation. No experimental results or numbers are reported.

[Allen et al 86 86] Kennedy and his associates report on the results of their work at Rice. Very little increase in vectorization is found after the-application of GMOD sets, GUSE sets, and constant propagation. Aliasing effects are found to be unimportant to the programs under consideration. The analysis proves useful only as part of FTOOL, an interactive tool for finding parallelism in programs.

[Ball 79] Ball presents a technique for predicting how much improvement would be gained in a given program if constant folding and test elision were applied to the program.

[Barnerjee 86] A review of Triolet’s work on parallelization of call statements in a multiprocessor environment.

[Banning 79] The classic algorithm for practical interprocedural analysis, later adapted by Cooper.

[Barth 77] Single-pass algorithm for finding interprocedural “may” summary information.

[Barth 78] This algorithm for finding inter-procedural summary information is said to be “precise up to symbolic execution.”

[Burke 84] Burke calculates MOD information and derives USE and REF. He makes the observation that summary information is of no great help in optimizing programs on a sequential machine architecture.

[Burke & Cytron 86] Interprocedural dependence analysis and parallelization in a multiprocessor environment.

[Callahan et al 86] An algorithm to help implement constant propagation.

[Chow & Rudnik 82] An algorithm for determining aliases in programs.

[Cooper 83] A proposal for a project that would use inter-procedural information to aid program design and construction.

[Cooper 85] A set of techniques for analyzing aliasing patterns.

[Cooper & Kennedy 84] A study of Banning’s algorithm. The original algorithm is decomposed into two subproblems, each of which has an efficient solution. Running time improves, from $O(\text{nodes} \times \text{edges})$ to “nearly linear.” A later paper corrects a couple of flaws in the logic [Cooper & Kennedy 87a].

[Cooper et al 86a] For use in an incremental compilation environment. The paper presents a test for determining which procedures in a program must be recompiled following an editing session.

[Cooper et al 85] A description of the IRP Programming Environment. No numbers are reported.

[Cooper et al 86b] Another description of the IRP Programming Environment. No numbers are reported.
An algorithm for finding aliases, retargetable for different machines/languages. Pointers are handled as well as ref parameter aliasing. The algorithm was implemented for C, Pascal, COBOL, and FORTRAN/77. The optimizer gets impressive results; it is not clear how much program speedup is due to alias analysis. Plans are made to integrate the algorithm into an inter-procedural global optimizer, which includes “handling of pointer alias set initialization, side effects of procedure calls, and the binding of formal and actual parameters.” It will be interesting to see if they gain any speedup.

Using data flow algorithms to search for programming errors.

A new approach to data flow analysis of procedural programs and programs with recursive data structures is described. The method depends on simulation of the interpreter for the subject programming language using a retrieval function to approximate a program’s data structures.

A method for identifying and reducing the hazards caused by aliasing. Also see [Rosen 79].

A data base for program flow information, implemented in LISP.

Using interprocedural analysis to perform elimination of redundant expressions.

Solves Banning’s algorithm [Banning 79] by dividing it into two subproblems, much as Cooper and Kennedy do later [Cooper & Kennedy 84]. Myers uses transitive closure to solve the subproblem dealing with aliases, and his solution is consequently slower than that of Cooper and Kennedy.

Where Banning [Banning 79] and an earlier Myers paper present algorithms for computing may information, this paper looks at the remaining problems of live, avail, and must-summary.

A bibliography of work in interprocedural analysis to June 1987.

A less readable form of [Rosen 79].

The interprocedural algorithm presented here derives information specific to each procedure call. Similar to Lomet [Lomet 77], except better in that it obtains the “sharpest possible local information.”

Incremental ipa in the style of the IR^n environment. The Rutgers version is called ISMM.

A not-very-in-depth discussion of some problems in PL/I, including side effects due to aliasing, pointers, label variables, and procedure invocations.

A description of the optimizing compiler used in the IR^n programming environment,

Triolet presents a method of parallelizing CALL statements in FORTRAN.

Direct parallelization of CALL statements; more of Triolet’s work. The algorithm uses the new objects Region and Execution Context.

Wall describes his algorithm for global (interprocedural) allocation at program link time. Only local variables are allocated to registers. Profile information is used to find out the usage frequency of each local variable.

An algorithm for handling the problem of procedure variables, label variables, and general aliasing relationships.

Weiser presents the concept of program slicing. In program slicing, one concentrates on one data flow problem at a time; parts of the program not related to the given problem are “sliced” away in order to simplify the problem.
References

Compilers, Principles, Techniques and Tools.

[Allen 74] Allen, F. E.
Interprocedural Data Flow Analysis.

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