A Direct Active Set Algorithm for Large Sparse Quadratic Programs with Simple Bounds*

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Abstract: We show how a direct active set method for solving definite and indefinite quadratic programs with simple bounds can be efficiently implemented for large sparse problems. All of the necessary factorizations can be carried out in a static data structure that is set up before the numeric computation begins. The space required for these factorizations is no larger than that required for a single sparse Cholesky factorization of a matrix with the same sparsity structure as the Hessian of the quadratic. We propose several improvements to this basic algorithm: a new way to find a search direction in the indefinite case that allows us to free more than one variable at a time and a new heuristic method for finding a starting point. These ideas are motivated by the two-norm trust region problem. Additionally, we also show how projection techniques can be used to add several constraints to the active set at each iteration. Our experimental results show that an algorithm with these improvements runs much faster than the basic algorithm for positive definite problems and finds local minima with lower function values for indefinite problems.

Keywords: quadratic programming, large sparse minimization, active set methods, trust region methods, sparse matrix updates, sparse matrix factorization, simple bounds, box constraints

Subject Classification: AMS/MOS: 65K05, 90C20, 65K10, 65F30

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1 Introduction

1.1 The problem

In this paper we are interested in minimizing a quadratic subject to simple bounds

$$\begin{gathered}\min \tfrac{1}{2}x^T Ax + b^T x \\ l \leq x \leq u,\end{gathered} \tag{1}$$

where A is an $n \times n$ symmetric matrix that is not necessarily positive definite. In particular, we are interested in the case where A is large and sparse. If A is positive definite, this problem can be solved in polynomial time by an interior point algorithm [22]. However, for general A, this problem is NP-hard [19]. The algorithms we consider are not polynomial. They work for both indefinite and positive definite quadratics, but in the indefinite case, they find only local minima.

We show how a direct active set method for solving definite and indefinite quadratic programs with simple bounds, typical of the dense algorithms of Fletcher [11] and Gill and Murray [14], can be efficiently implemented for large sparse problems. All of the necessary factorizations can be carried out in a static data structure that is set up before the numeric computation begins. The space required for these factorizations is no larger than that required for a single sparse Cholesky factorization of a matrix with the same sparsity structure as A. Since our algorithm solves the linear systems directly, rather than using iterative methods, poorly conditioned matrices are not a problem. We propose several improvements to this basic algorithm: a new way to find a search direction in the indefinite case that allows us to free more than one variable at a time and a new heuristic method for finding a starting point. These ideas are motivated by the two-norm trust region problem. Additionally, we also show how projection, or 'bending', techniques can be used to add several constraints to the active set at each iteration. Our experimental results show that an algorithm with these improvements runs much faster than the basic algorithm for positive definite problems and finds local minima with lower function values for indefinite problems.

Many authors have developed active set methods for solving (1). Our basic algorithm is based on the dense algorithms of Fletcher and Jackson [11] for solving (1) and of Gill and Murray [14] for solving the more general problem

$$\begin{gathered}\min \tfrac{1}{2}x^T Ax + b^T x \\ Cx \leq d.\end{gathered}$$

Calamai and Moré [3] and Moré [17] outlined an active set method that uses projected gradients to identify the active set and can be generalized to the sparse case. They did not fully specify the algorithm; in particular, they did not specify a choice of starting point or search direction for the indefinite case, or details of a sparse implementation. To solve (1) when A is sparse, Dembo and Tulowitzki [7] proposed several active set methods with inexact subspace minimization, using both projected gradient steps and conjugate gradients steps. We use exact subspace minimization and solve our linear systems directly. Björck [2] proposed an active set algorithm for the sparse least squares problem

$$\begin{gathered}\min \tfrac{1}{2}x^TC^TCx + d^Tx \\ l \le x \le u\end{gathered}$$

that is similar to our algorithm of Section 2. His algorithm only considered the case where the matrix $A = C^TC$ is positive definite but it does not form A; the algorithms we consider also allow A to be indefinite.

The organization of our paper is as follows. The rest of this section introduces notation and provides some background material. Section 2 describes a straightforward active set algorithm and provides a proof of its convergence. Section 3 provides the details of a sparse implementation of this algorithm. Section 4 describes several techniques that can be used to improve the performance of our basic algorithm. Section 5 describes our computer implementation, suggests several algorithms that use the improvements outlined in Section 4, and presents numerical results to compare these algorithms. Section 6 presents our conclusions and ideas for future work.

1.2 Some Notation and Background Material

We let c_{ij} denote the ijth entry of a matrix C, c_{*i} the ith column of C, and c_{i*}^T the ith row of C. We let $c_{\wedge i}$ denote the top part of the ith column of C, where top part should be obvious from context. Similarly, we let $c_{\vee i}$ denote the bottom part of the ith column of C. The expression $C > 0$ means that C is positive definite; similarly $C \ge 0$ means that C is positive semi-definite. We let I denote the identity matrix, and e_i the ith column of I. If $S = \{s_1, \ldots, s_k\}$ is a subset of the first n integers that is maintained as an ordered list, we define Z_S as the matrix of columns $(e_{s_1}, \ldots, e_{s_k})$. We let $|S|$ denote the size of S.

To simplify our presentation, we note that through a suitable scaling and translation we can rewrite (1) in a simpler form as

$$\begin{gathered}\min \tfrac{1}{2}x^TAx + b^Tx \\ -1 \le x \le 1.\end{gathered} \tag{2}$$

Henceforth we assume the problem is in this form.

The variables with values of 1 or -1 we call variables *at their bound.* In our active set algorithm, the set B of variables at their bound that we are holding fixed we call *bound* variables. These variables correspond to the *active* constraints, those satisfied with equality that we are forcing to remain satisfied. When we *bind* a variable we add it to the set of bound variables. The set F of variables which are not bound variables we call *free* variables. When we free a variable, we add it to the set of free variables. Note that $F = \{1, \ldots, n\} - B$.

We let $g(x)$ denote the gradient at the current point, $g(x) = Ax + b$, or simply g if x is apparent from context. We define the reduced quantities

$$A_F = Z_F^TAZ_F, \quad g_F = Z_F^Tg, \quad g_B = Z_B^Tg, \quad x_F = Z_F^Tx, \quad x_B = Z_B^Tx.$$

Note that because of the structure of Z_F and Z_B, the reduced quantities are just submatrices and subvectors of the original quantities. To simplify our discussion, if $F = \emptyset$, although A_F is not really defined, we consider A_F to be positive definite. We call x a *constrained stationary point* if $g_F(x) = 0$. We let $q(x) = \frac{1}{2}x^T Ax + b^T x$ and $q_F(s) = q(x + Z_F s) - q(x) = \frac{1}{2}s^T A_F s + g_F^T s$. Thus the quadratic $q_F(s)$ defined at the point x is a measure of the change in q from the point x to the point $x + Z_F s$.

Let x^* be the current point, let B^* be the set of all variables at a bound and let F^* be the set of all variables not at a bound. Then the following conditions are necessary for x^* to be a local minimum:

$$\begin{array}{rl} \text{feasibility:} & -1 \leq x^* \leq 1, \\ \text{first order:} & \begin{cases} g(x^*)_i = 0 & \text{if } -1 < x_i^* < 1, \\ g(x^*)_i \leq 0 & \text{if } x_i^* = 1, \\ g(x^*)_i \geq 0 & \text{if } x_i^* = -1, \end{cases} \\ \text{second order:} & A_{F^*} \geq 0. \end{array} \tag{3}$$

These are not sufficient conditions however. If we assume that x^* is *non-degenerate*, i.e., $g(x^*)_i \neq 0$ for all $i \in B^*$, then the following conditions are sufficient to guarantee that x^* is a local minimum:

$$\begin{array}{rl} \text{feasibility:} & -1 \leq x^* \leq 1, \\ \text{first order:} & \begin{cases} g(x^*)_i = 0 & \text{if } -1 < x_i^* < 1, \\ g(x^*)_i < 0 & \text{if } x_i^* = 1, \\ g(x^*)_i > 0 & \text{if } x_i^* = -1, \end{cases} \\ \text{second order:} & A_{F^*} > 0. \end{array} \tag{4}$$

The algorithm we present converges to a point that satisfies (3) with $A_{F^*} > 0$. If x^* is non-degenerate, then we are guaranteed that x^* is a local minimum, since (4) is satisfied. Fletcher [10] showed that if x^* is degenerate then x^* is a local minimum of a nearby problem, one with a slightly perturbed b. Murty and Kabadi [19] showed that if x^* is degenerate then the problem of detemining whether or not x^* is a local minimum is NP-hard.

Notice that if x^* solves (2) then it also solves the equality constrained problem

$$\begin{gathered} \min \tfrac{1}{2}x^T Ax + b^T x \\ x_{B^*} = x_{B^*}^*. \end{gathered}$$

So if we knew the correct active set, we would need only to solve an unconstrained problem. This observation forms the basis for the active set methods. At each iteration, these methods hold a subset of the variables fixed at a bound, and they attempt to minimize $q(x)$ in the space of the remaining variables, subject to the bounds on these variables. They continue adding variables to the active set until they minimize $q(x)$ with some active set. If the necessary conditions (3) show that this point is not a local minimum of (2) they remove some of the active constraints and repeat.

2 A Basic Active Set Algorithm

2.1 The Algorithm

In this Section, we describe an active set algorithm *GSA*, based on the dense algorithms by Fletcher and Jackson [11] and Gill and Murray [14], and outlined in Figure 1. The details of the sparse implementation are presented in the next section.

The first step of the algorithm is to find a permutation matrix P and update A via $A = PAP^T$ and b via $b = Pb$. Choose P to reduce the number of nonzeroes in the Cholesky factor of a positive definite matrix with the sparsity structure of A. Finding an optimal P is an NP-complete problem [21], so we must rely on heuristics for this step. For simplicity, we will call this new ordering of A the original ordering.

The next step of the algorithm is to find a free set F on which A_F is positive definite. Although we refer to F as a set, we maintain F as an ordered list so that A_F is well-defined. Initialize $F := \{1, \ldots, n\}$ and begin the Cholesky factorization of the matrix A_F. If, at the ith step of Cholesky, a positive element occurs on the diagonal then set $x_i := 0$ and continue the factorization. If a nonpositive element occurs, remove i from F, exclude row and column i from the Cholesky factorization, and set x_i equal to whichever bound yields the smallest value when substituted into the one dimensional quadratic $\frac{1}{2}a_{ii}x_i^2 + b_i x_i$. At the end of the Cholesky factorization, x is the starting point, F is the desired free set (possibly the empty set), and we have the Cholesky factorization of A_F. Note that in the case where $A = \mathrm{diag}(a_{ii})$ and $a_{ii} \le 0$, x is the global solution to (2).

The next step is to find a constrained stationary point. If x is not already a constrained stationary point, perform the following sequence of steps. Compute the Newton direction s by solving $A_F s = -g_F$. Update x via the formula $x := x + \alpha Z_F s$, where $0 \le \alpha \le 1$ is chosen as large as possible without violating a constraint. If the Newton step is feasible, i.e., $\alpha = 1$, then x is a constrained stationary point. Otherwise remove from F any variables that have reached a bound and update the Cholesky factorization of A_F. If x is not a constrained stationary point, repeat the preceding sequence of steps until such a point is reached.

Now determine if the constrained stationary point x is indeed an optimal point. If all of the components of $g_B(x)$ have the correct sign according to (3), then x is an optimal point. Otherwise, find the bound variable, say t, corresponding to the component of g_B that is largest in magnitude and has the incorrect sign. Update F by adding t to the end of it. Let F' be the value of F before it is updated. Solve $L_{F'} r = Z_{F'} a_{*t}$ for r and set $\tau := a_{tt} - r^T r$. If $\tau > 0$ then A_F is positive definite and its Cholesky factorization is

$$L_F = \begin{pmatrix} L_{F'} & \\ r^T & \sqrt{\tau} \end{pmatrix}.$$

If $\tau \le 0$ then A_F is not positive definite, so its Cholesky factorization is not defined, but $A_F = L_F D L_F^T$ where

$$L_F = \begin{pmatrix} L_{F'} & \\ r^T & 1 \end{pmatrix}$$

and $D = \mathrm{diag}\,(1, \ldots, 1, \tau)$.

If x is not a constrained stationary point or A_F is not positive definite, perform the following sequence of steps. We have two cases.

If A_F is positive definite, compute the Newton direction s by solving $A_F s = -g_F$. Set $x := x + \alpha Z_F s$, where $0 \leq \alpha \leq 1$ is chosen as large as possible without violating a constraint. If the Newton step is feasible, i.e., $\alpha = 1$, x is a constrained stationary point and A_F is positive definite. Otherwise remove from F any variable that has reached a bound and update the Cholesky factorization of A_F.

If A_F is not positive definite, find a nonascending search direction as follows. Solve $L_F^T \tilde{s} = e_m$, where $m = |F|$ and set s to be $\tilde{s}$ or $-\tilde{s}$ so that $g_F^T s \leq 0$. Note that s is a direction of nonpositive curvature since $s^T A_F s = \tau \leq 0$. Set $x := x + \alpha Z_F s$, where $\alpha \geq 0$ is chosen as large as possible without violating a constraint. Remove from F any variable that has reached a bound and update the LDL^T factorization of A_F.

If x is not a constrained stationary point or A_F is not positive definite, repeat the preceding sequence of steps.

Now x is a constrained stationary point and A_F is positive definite. If $t \in F$ reorder the elements of F so that they are in their original order and update the Cholesky factorization of A_F so that it corresponds with this order. As we shall see in Section 3, this is necessary for an efficient sparse implementation. If x is not optimal proceed as above. If x is optimal, reorder x via $x := P^T x$.

2.2 A Proof of Convergence

In this section we prove that *GSA* converges. The proofs refer to the algorithm *GSA* as outlined in Figure 1 and described in detail in Section 2.1. They are typical of those used to show convergence of active set methods.

Lemma 2.1 *Execution of the first while loop and each repeat loop in the second while loop must terminate in a finite number of steps.*

Proof: This is immediate, since there are only $|F|$ variables that can be bound and for each search direction, we either bind a variable or terminate the loop by stepping to a constrained stationary point. ■

Lemma 2.2 *The function value of each constrained stationary point is lower than that of the previous one.*

Proof: Let $\hat{x}$ be a constrained stationary point and let $\hat{F}$ be the value of the free set F at $\hat{x}$. So $g_{\hat{F}} = 0$. Consider the second while loop in *GSA*. We free a variable, say t. Then after updating F we have $g_F = \beta e_m$, where $m = |F|$ and $\beta \neq 0$. Suppose we take a step of length 0. This implies that we bind a variable. The variable that we bind cannot be the variable t, since the fact that $-g_F = -\beta e_m$ is a feasible nonascending direction and that $g_F^T s \leq 0$ imply that $s_m e_m$ is a feasible nonascending direction. After binding the variable and updating F, we still have $g_F = \beta e_m$, where $m = |F|$. Thus we have not reached a constrained stationary point so the loop will not terminate. We can take steps of length 0 at most r times, where r is the number of variables at their bound

Find a permutation matrix P and reorder the matrix A via $A := PAP^T$ and the vector b via $b := Pb$.

Using a greedy approach during the computation of the Cholesky factorization of A, find a starting point and a free set F such that A_F is positive definite.

{ Find an initial constrained stationary point. }

while not at a constrained stationary point **do**

  compute Newton step.

  if Newton step is feasible take it.
  otherwise follow Newton direction until a constraint becomes active;
  bind corresponding variable and update factorization.

enddo

{ Find an optimal point. }

while constrained stationary point is not optimal **do**

  free one of the bound variables corresponding to a component of the gradient that has the incorrect sign according to (3);
  update factorization.

  repeat

    if A_F is positive definite **then**

      compute Newton step.
      if Newton step is feasible take it.
      otherwise follow Newton direction until a constraint becomes active;
      bind corresponding variable and update factorization.

    else

      compute nonascending search direction of negative or zero curvature.

      follow search direction until a constraint becomes active;
      bind corresponding variable and update factorization.

    endif

  until at constrained stationary point where $A_F > 0$.

  if neccesary, reorder F and update factorization.

enddo

Reorder x via $x := P^T x$.

Figure 1: A General Sparse Active set Algorithm *GSA*

in $\hat{F}$. Then we must take a step of positive length, so $\alpha > 0$. We now show that this step decreases the function value. We have two cases, depending on how we generate s.

Case 1 A_F is positive definite.
Then s solves $A_F s = -g_F(x)$ and $\alpha \leq 1$. So

$$q(x + \alpha Z_F s) - q(x) = (\frac{\alpha^2}{2} - \alpha)(g_F^T A_F^{-1} g_F) < 0.$$

Case 2 A_F is not positive definite.
We compute s by solving $L_F^T s = \pm e_m$. Since L_F^T is upper triangular and nonsingular, $s_m \neq 0$. By our choice of the sign of s, $g_F^T s = \beta e_m^T s = \beta s_m < 0$. So

$$q(x + \alpha Z_F s) - q(x) = \alpha g_F^T s + \frac{\alpha^2}{2} s^T A_F s < 0.$$

Therefore we have decreased the function value. In each subsequent step we are never increasing the function value since either we are following the Newton direction, i.e., we are stepping toward the global minimum of the quadratic q_F, or we are following a non-ascending direction of nonpositive curvature. Thus the next constrained stationary point has a strictly lower function value than the previous constrained stationary points. ∎

Theorem 2.3 *The algorithm GSA converges to a point satisfying (3) with $A_F > 0$ in a finite number of steps.*

Proof: Finding an initial free set is obviously a finite procedure. By Lemma 2.1, execution of the first while loop and each repeat loop in the second while loop terminates in a finite number of steps. Each constrained stationary point is a global, although not necessarily unique, solution to an equality constrained problem. By Lemma 2.2 the function value of each constrained stationary point is lower than the values of all previously found points. Since there are only finitely many equality constrained problems, we cannot cycle and must eventually terminate. When we terminate, $g_F = 0$, $A_F > 0$, and the signs of the components of g_B satisfy (3), so the algorithm *GSA* converges to a point with the desired properties in a finite number of steps. ∎

3 A Sparse Implementation

3.1 The Data Structure

A major portion of the work in the *GSA* algorithm involves computing and updating the Cholesky factorization. The following three steps are typically employed in computing the Cholesky factorization of a sparse matrix [12].

1. Find a permutation matrix P and form PAP^T. Choose P to reduce the number of nonzeroes in L.
2. Symbolically factor A to determine the positions of the nonzeroes in L. Use this information to allocate storage for L.
3. Numerically factor A.

In this section we show that we can perform the first two steps for the matrix A and use the resulting data structure to store each subsequent L_F.

In designing a data structure for sparse matrices, we want to store only the nonzeroes with their row and column indices in a way that allows us to access them easily. Typically, one stores the nonzeroes consecutively in an array by columns (rows), with a pointer to the beginning of each column (row) and a corresponding array of row (column) indices. We need to show that such a structure set up for L contains the necessary row and column indices to store L_F. To do this, instead of labeling the rows and columns of the matrices A_F and L_F with consecutive numbers, we label them according to the row and column of A from which they came. For example, if $F = \{2, 4, 6, 9\}$, then the rows of A_F are labeled 2, 4, 6, 9. This convention will be very important in updating the Cholesky factorization.

To exploit the sparsity of a matrix, it is often helpful to view the matrix as a graph. To this end, we provide some useful definitions from graph theory. See George and Liu [12] for a more thorough discussion of this material. We define a *graph* $G = (V, E)$ as a set of vertices V and a set of edges E. An *edge* (v, w) is an unordered pair of distinct vertices. A *path* from v to w in G is a sequence of distinct vertices $v = v_0, v_1, \ldots v_k = w$ such that $(v_i, v_{i+1}) \in E$ for $i = 0, 1, \ldots, k-1$. We can represent the nonzero structure of an $n \times n$ symmetric matrix A with a graph $G(A) = (V, E)$ where $V = \{v_1, v_2, \ldots v_n\}$ are the labels of the rows of A and $(v_i, v_j) \in E$ if and only if $a_{ij} \neq 0$ and $i \neq j$.

We can predict the nonzero structure of the Cholesky factor L of a symmetric matrix A using the graph $G(A)$. Assuming no exact numerical cancellation, Rose, Tarjan, and Lueker [20] proved the following lemma.

Path Lemma *Let i and j be integers with $i \geq j$. Then there exists a nonzero in position (i, j) of L if and only if there exists a path in $G(A)$ from i to j through vertices numbered lower than j.*

We let $\eta(L)$ denote the set of nonzero positions in L that are predicted by the Path Lemma. We call these positions the *structural* nonzeroes. We define

$$\eta(l_{*j}) = \{i \mid (i, j) \in \eta(L)\}$$

and

$$\eta_k(l_{*j}) = \{i \mid i \geq k \text{ and } (i, j) \in \eta(L)\}.$$

For a general vector v, we let $\eta(v)$ denote the set of nonzero positions of v.

We can now prove the first theorem, which says that if entry (i, j) of L_F is nonzero, then entry (i, j) of L is nonzero. This result follows easily from the Path Lemma and has been observed independently by Björck [2].

Theorem 3.1 *If* $(i,j) \in \eta(L_F)$ *then* $(i,j) \in \eta(L)$.

Proof: If $(i,j) \in \eta(L_F)$, then there exists a path in $G(A_F)$ from i to j through vertices numbered lower than j. But since $\eta(A_F) \subset \eta(A)$, there must also exist a path in $G(A)$ from i to j through vertices numbered lower than j. So $(i,j) \in \eta(L)$. ∎

The next subsections describe the data structure manipulations necessary for the computations we will be performing. Henceforth we will assume that the nonzeroes are stored consecutively in an array by columns, with a pointer to the beginning of each column and a corresponding array of row indices. By Theorem 3.1, this data structure is adequate to store L_F for any F.

3.2 Binding a Variable

In this section we show how to update the Cholesky factorization when we delete a variable from the free set. Suppose F' is the current free set and F is the free set obtained from F' by deleting the variable t. Let $F' = \{f_1, f_2, \ldots, f_s, \ldots, f_m\}$, where $m = |F|$ and $f_s = t$. Then the matrix A_F is obtained from $A_{F'}$ by deleting row and column t of $A_{F'}$. We want to see how to obtain L_F from $L_{F'}$.

Let us partition $A_{F'}$ and $L_{F'}$ along row and column t as follows.

$$A_{F'} = \begin{pmatrix} A_{11} & a_{\wedge t} & A_{12} \\ a_{\wedge t}^T & a_{tt} & a_{\vee t}^T \\ A_{21} & a_{\vee t} & A_{22} \end{pmatrix}$$

$$L_{F'} = \begin{pmatrix} L_{11} & & \\ l_{\wedge t}^T & l_{tt} & \\ L_{21} & l_{\vee t} & L_{22} \end{pmatrix}.$$

Then we can write A_F as

$$A_F = \begin{pmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{pmatrix}.$$

By deleting row t from $L_{F'}$ we obtain the lower Hessenberg matrix

$$H = \begin{pmatrix} L_{11} & & \\ L_{21} & l_{\vee t} & L_{22} \end{pmatrix}$$

with the property that $HH^T = A_F$. We can obtain L_F from H by applying Givens rotations to the column pairs (t, f_{s+1}), $(f_{s+1}, f_{s+2}), \ldots, (f_{m-1}, f_m)$.

Recall that we are labeling each column of L_F according to the corresponding column of A, since we will be storing column j of L_F in that part of the data structure set up for column j of L. Thus the (2,2) block of L_F will be stored in the same space as the (2,2) block of $L_{F'}$. If we applied the Givens rotations as above, the (2,2) block of L_F would be in columns t through f_{m-1} instead of columns f_{s+1} through f_m. However, suppose we apply Givens rotations to the column pairs (t, f_{s+1}), $(t, f_{s+2}), \ldots, (t, f_m)$ of H to zero out column $l_{\vee t}$, i.e.,

$$H' = HG = \begin{pmatrix} L_{11} & & \\ L_{21} & 0 & L'_{22} \end{pmatrix},$$

where G is the matrix of Givens rotations. Then $H'H'^T = A_F$ and the (2,2) block of H' is where we want it, in columns f_{s+1} through f_m. These are the Givens rotations we will apply in our sparse setting. Since $l_{\vee t}$ is in general sparse, we do not need to rotate column $l_{\vee t}$ with every column of L_{22}.

Thus, to obtain L_F from $L_{F'}$ we proceed as follows. Let t be the variable leaving the free set. First, copy column t of $L_{F'}$ into a dense intermediate column vector v. Since we are deleting row t from L_F, place a zero in position t of v. Next, zero out the first nonzero position, say position j, of v with column j by applying Givens rotations to the two columns. Now zero out each subsequent nonzero position of v with the appropriate column. The *BindVar* algorithm in Figure 2 contains the details.

$v = l_{*t}$

while there are nonzeros in v **do**

  $j =$ first nonzero position in v

  compute and apply Givens rotation G such that

  $(v_j \;\; l_{jj})\,G^T \;=\; (0 \;\; (v_j^2 + l_{jj}^2)^{1/2})$

  for each $i \in \eta(l_{*j})$ **do**

    $(v_i \;\; l_{ij}) = (v_i \;\; l_{ij})\,G^T$

  enddo

enddo

Figure 2: The *Bindvar* Algorithm

Consider the algorithm *BindVar.* Suppose we are rotating the intermediate column v with column j to zero out position j of v. Since Theorem 3.1 implies that the structure of the jth column of L_F is contained in the structure of the jth column of $L_{F'}$, v must have zeroes in positions where column j has structural zeroes. Therefore we can rotate column j with v by operating only on the structural nonzeros in column j and the corresponding positions in v. Thus we can apply the Givens rotations to $L_{F'}$ to obtain L_F in time proportional to the number of nonzeros in L_{22}.

We will show that the fact that v has zeroes in positions where column j has structural zeros is a structural property. This means that these zeroes in v are also structural zeroes, i.e., they did not occur due to numerical cancellation. The proof is based on the following lemma.

Lemma 3.2 *Let j and k be integers satisfying $0 < j < k \leq n$. Then*

$$k \in \eta(l_{*j}) \Rightarrow \eta_k(l_{*j}) \subseteq \eta(l_{*k})$$

Proof: Let $k \in \eta(l_{*j})$ and suppose $i \in \eta_k(l_{*j})$. Hence, $i \geq k > j$. By the Path Lemma there exists a path in $G(A)$ from v_j to v_i through vertices numbered lower than j. Since $k \in \eta(l_{*j})$, there is also a path from v_j to v_k through vertices numbered lower than j.

Patching these two paths together, we get a path from v_k to v_i through vertices numbered lower than k, and hence $i \in \eta(l_{*k})$. ∎

Theorem 3.3 *In the algorithm BindVar, let $j(k)$ denote the value of the variable j during the kth iteration, and define $j(0) = t$. Then at the pth iteration of the while loop of BindVar, after the first assignment statement, we have*

$$\eta(v) = \eta_{j(p)}(l_{*j(p-1)}) \text{ and}$$
$$\eta(v) \subseteq \eta(l_{*j(p)}).$$

Proof: The proof is by induction. After the first assignment statement in the first pass through the loop, $v = l_{*t}$, so by Lemma 3.2 the result is true. Assume it is true for k passes through the loop. After the first assignment statement of the kth pass, the induction hypothesis tells us that

$$\eta(v) = \eta_{j(k)}(l_{*j(k-1)}).$$

Since $j(k) \in \eta(v)$, we have $j(k) \in \eta(l_{*j(k-1)})$, so Lemma 3.2 implies

$$\eta_{j(k)}(l_{*j(k-1)}) \subseteq \eta(l_{*j(k)}).$$

Therefore

$$\eta(v) \subseteq \eta(l_{*j(k)}).$$

So upon completion of the kth pass, we have

$$\eta(v) = \eta(l_{*j(k)}) - \{j(k)\}.$$

After the first assignment statement of the $k+1$st pass, we have $\eta(v) = \eta_{j(k+1)}(l_{*j(k)})$ and $\eta(v) \subseteq \eta(l_{*j(k+1)})$, by Lemma 3.2. So the result is true for $k+1$ passes through the loop. ∎

3.3 Reordering the Free Set

Suppose at the end of the second while loop in *GSA* we need to reorder the free set and update the Cholesky factorization. This occurs when t, the last variable we freed, is still in the free set when the next constrained stationary point is found. Let $F' = \{f_1, f_2, \ldots, f_m, f_s\}$ denote the current free set, where $m+1 = |F'|$ and $f_s = t$, and let F be the free set after F' is reordered. We will show how to obtain L_F from $L_{F'}$.

Let $(r^T \ \tau)$ be the last row of $L_{F'}$, corresponding to row t of the matrix A. Let us partition $L_{F'}$ into blocks,

$$L_{F'} = \begin{pmatrix} L_{11} & & \\ L_{21} & L_{22} & \\ r_\wedge^T & r_\vee^T & \tau \end{pmatrix},$$

by grouping together rows and columns with labels less than t and rows and columns with labels greater than t. If we reorder the rows and columns of $L_{F'}$ to correspond with the ordering of F then we obtain the matrix

$$H = \begin{pmatrix} L_{11} & & \\ r_\wedge^T & \tau & r_\vee^T \\ L_{21} & 0 & L_{22} \end{pmatrix}$$

with the property that $HH^T = A_F$. Here, H is a lower triangular matrix with a horizontal spike in row t. We can obtain L_F from H by zeroing out the entries of $r_\vee^T$ from right to left using column t. That is, we apply Givens rotations to the column pairs (t, f_m), $(t, f_{m-1}), \ldots, (t, f_{s+1})$ to zero out the entries of $r_\vee^T$. However, since r is in general a sparse vector, we only need to rotate those columns whose component of $r_\vee$ is nonzero.

Thus, to obtain L_F from $L_{F'}$ we proceed as follows. Let t be the variable that is out of order in F'. Zero out a dense intermediate vector v that will be used to accumulate column t of L_F. Now use Givens rotations to zero out the nonzero entries in r which have labels greater than t, proceeding from right to left. The *Reorder* algorithm in Figure 3 contains the details.

Since Theorem 3.1 implies that the structure of the jth column of L_F is contained in the structure of the jth column of $L_{F'}$, when we rotate v with column j, v must have zeroes in positions where column j has structural zeroes. Therefore we can rotate column j with v by operating only on the structural nonzeros in column j and the corresponding positions in v. Thus we can apply the Givens rotations to H to obtain L_F in time proportional to the number of nonzeros in L_{22}.

The fact that when we rotate v with column j, v must have zeroes in positions where column j has structural zeroes is not a structural property, i.e., numerical cancellation occurs to create these zeroes. However since computing Cholesky factorizations, solving triangular systems, and computing and applying Givens rotations are numerically stable processes, this will not cause any numerical difficulties.

4 Improving the Basic Algorithm

In what follows we describe several possible modifications to *GSA*. The algorithm *GSA* binds and frees only one variable at a time. Because of this, it runs very slowly on large sparse problems. In Section 4.1, we show that by projecting each direction, we can bind several variables for each search direction. However because of the way *GSA* computes search directions, it cannot free more than one variable at a time. In Section 4.2, we propose a new method for computing search directions that allows us to free more than one variable at a time. For this technique, A_F need not remain positive definite. In light of this, we present a heuristic method for finding an starting point and an initial active set in Section 4.4. We can combine these techniques in various ways and use them in one or both while loops of *GSA*. We defer discussion of these possibilities to Section 5, where we present some numerical results to compare them.

$v = 0$

while there are nonzeros in $r_\vee$ **do**

$j =$ last nonzero position in $r_\vee$

compute and apply Givens rotation G such that

$(\,\tau \;\; r_j\,)\,G = (\,(\tau^2 + r_j)^{1/2} \;\; 0\,)$

for each $i \in \eta(l_{*j})$ **do**

$(\,v_i \;\; l_{ij}\,) = (\,v_i \;\; l_{ij}\,)\,G$

enddo

enddo

$l_{*t} = v$

Figure 3: The *Reorder* Algorithm

4.1 Projecting the Descent Direction

The algorithm described in the previous section does a lot of work for each variable it binds; in particular, it updates the Cholesky factorization of L_F, solves a linear system, and performs a matrix vector multiply to update g_F. Thus, we considered using each search direction to bind several variables. This idea has been used by many authors [1,3,5] and is outlined below.

Follow the search direction until a constraint is violated and remove the corresponding variable from the free set. Now project the search direction onto the space of free variables. If this direction is a descent direction follow it until a local minimum along it is reached or a constraint becomes active. Continue projecting the direction until it is no longer a descent direction or a local minimum along that direction has been reached. Then compute a new search direction.

To formalize this, we introduce the notation of a projection operator Π defined componentwise by

$$[\Pi(x)]_i = \begin{cases} -1 & \text{if } x_i \le -1 \\ x_i & \text{if } -1 < x_i < -1 \\ 1 & \text{if } x_i \ge 1. \end{cases}$$

Given a current point x and a descent direction s, we update x via

$$x := \Pi(x + \alpha s),$$

where $\alpha > 0$ is the first local minimum of $q(\Pi(x + \alpha s))$. Conn, Gould and Toint [6] give a very efficient algorithm for finding such a local minimum, requiring one sparse matrix-vector multiplication and two vector inner-products to begin, and two sparse inner products for each variable bound.

4.2 Handling Indefiniteness

In this section we present an algorithm for obtaining a search direction when A_F is indefinite that allows us to free many variables at each iteration. This algorithm uses global information in the sense that it chooses a step in the direction of an approximate global minimum of q_F in a circle centered at our current point.

Suppose in computing the Cholesky factorization of A_F, we find that A_F is not positive definite. Assume we can compute α such that $(A_F + \alpha I)$ is positive definite. Let $s(\alpha) = -(A_F + \alpha I)^{-1} g_F$ and $\Delta = \|s(\alpha)\|_2$. Then $s(\alpha)$ is the unique global solution to the problem

$$\begin{aligned} &\min \tfrac{1}{2} s^T A_F s + g_F^T s \\ &\|s\|_2 \leq \Delta. \end{aligned} \tag{5}$$

Thus $s(\alpha)$ minimizes $q_F(s)$ in a circle of radius $\|s(\alpha)\|_2$ from our current point. Since $(A_F + \alpha I)$ is positive definite, $s(\alpha)$ is a descent direction of q_F and therefore of q. If $\|s(\alpha)\|_2$ is small enough, then $s(\alpha)$ seems like a reasonable choice for our search direction. For example, we may require that $\|s(\alpha)\|_2$ be less than twice the radius of the smallest circle that is centered at x and encloses the feasible region. If $\|s(\alpha)\|_2$ is large enough that $\|x + Z_F s(\alpha)\|_\infty \geq 1$ then we are guaranteed that if we follow $s(\alpha)$ we will continue descending until we violate a constraint.

However it may be the case that for all α that make $(A_F + \alpha I)$ positive definite, $\|x + Z_F s(\alpha)\|_\infty < 1$. Suppose this is the case. Let λ_1 be the smallest eigenvalue of A_F and $\hat{z^*}$ be an associated unit eigenvector. If Δ is greater than $\|s(\alpha)\|_2$ for all α that make $(A_F + \alpha I)$ positive definite, then the solution to the problem

$$\begin{aligned} &\min \tfrac{1}{2} s^T A_F s + g_F^T s \\ &\|s\|_2 \leq \Delta, \end{aligned} \tag{6}$$

is $s = (A_F - \lambda_1 I)^+ g_F + \sigma \hat{z^*}$, where $^+$ denotes pseudo-inverse, and σ is the root with the smaller norm of the quadratic $\|s(\sigma)\|_2^2 - \Delta^2$. In this case, which is commonly referred to as the *hard case*, we approximate the solution to (6) by first finding an α so that $(A_F + \alpha I)$ is positive definite and $s(\alpha)$ is almost as large as possible. Then we update our current point $x := x + Z_F s(\alpha)$, and choose our search direction to be $\hat{z}$, an approximation to $\hat{z^*}$ that is a nonascending direction and a direction of nonpositive curvature. This choice of step guarantees that we decrease the function value, since $g_F^T s(\alpha) < 0$, and that if we follow $\hat{z}$ until we violate a constraint we will not increase the function value.

In summary, we compute our search direction s as follows. Attempt the Cholesky factorization of A_F. If it succeeds, set $s := -A_F^{-1} g_F$. Otherwise, perform the following steps. Compute the direction of negative curvature $\hat{y}$ from the breakdown of Cholesky, as described in Section 2.1. Then compute $s(\alpha)$ and, if appropriate, $\hat{z}$, as described in the next section. Finally, if $\|x + Z_F s(\alpha)\|_\infty \geq 1$, then set $s := s(\alpha)$; otherwise, update $x := x + Z_F s(\alpha)$ and set $s := \hat{z}$.

4.3 Solving for the Descent Direction

To find the search directions of the previous section we need only slightly modify the trust region algorithm by Moré and Sorensen [18]. This algorithm finds an approximate solution of the problem

$$\begin{aligned} &\min \tfrac{1}{2}s^T C s + d^T s \\ &\|s\|_2 \leq \Delta, \end{aligned} \tag{7}$$

where C, d, and Δ are given. If there exists $\alpha \geq 0$ such that

$$\begin{aligned} (C + \alpha I) &> 0, \\ (C + \alpha I)s &= -d, \text{ and} \\ \|s\|_2 &= \Delta, \end{aligned} \tag{8}$$

then $s(\alpha)$ is the unique solution to (7). To find such an α, the trust region algorithm sets $s(\alpha) = -(C + \alpha I)^{-1} d$ and applies safeguarded Newton's method to solve

$$f(\alpha) = \frac{1}{\Delta} - \frac{1}{\|s(\alpha)\|_2} = 0. \tag{9}$$

Given an initial guess of α, it attempts the Cholesky factorization of $(C + \alpha I)$. If this factorization is successful, the algorithm uses it to compute the Newton step for (9) and then takes this step, subject to some safeguarding. However, if the Cholesky factorization breaks down, the algorithm modifies α and tries again. Since there is no convenient way of knowing when to use the hard case, i.e., when there is no α that solves (8), if a particular α yields $\|s(\alpha)\|_2 < \Delta$, then the algorithm tries the hard case. Using the Cholesky factorization of $(C + \alpha I)$, it computes $\hat{z}$, a unit approximation to an eigenvector associated with λ_1, the smallest eigenvalue of C. Then it computes σ, the root with smaller magnitude of the quadratic $\|s(\alpha) + \sigma\hat{z}\|_2^2 - \Delta^2$. This choice of σ guarantees that $\sigma\hat{z}$ is a nonascent direction of q_F at $x + Z_F s(\alpha)$. Finally, it determines if $s(\alpha) + \sigma\hat{z}$ satisfies the termination criteria. If not, it repeats the process with a new α.

We apply the trust region algorithm of Moré and Sorensen to the quadratic

$$\min \tfrac{1}{2}s^T A_F s + g_F^T s,$$

making two modifications. The algorithm requires a trust region size Δ and a tolerance γ, and terminates when

$$\alpha = 0 \text{ and } \|s(\alpha)\|_2 \leq \Delta^2, \tag{10}$$

$$\text{or } (1-\gamma)\Delta \leq \|s(\alpha)\|_2 \leq (1+\gamma)\Delta, \tag{11}$$

or, in the hard case, when

$$\begin{gathered} \|s(\alpha) + \sigma\hat{z}\|_2 = \Delta \text{ and} \\ \sigma^2 \hat{z}^T (A_F + \alpha I)\hat{z} \leq \gamma(2-\gamma)(s(\alpha)^T (A_F + \alpha I) s(\alpha) + \alpha\Delta^2). \end{gathered}$$

These conditions insure that the approximate solution satisfies

$$q(s(\alpha) + \sigma\hat{z}) - q(x^*) \leq \gamma(2-\gamma)|q(x^*)|,$$

where $q(x^*)$ is the global minimum of (7). We choose Δ to be $(1+\beta)$ times the diameter of the smallest circle that is centered at our current point and contains the feasible region, where $0 < \beta < \gamma$. To ensure that we generate a direction $s(\alpha)$ that descends until it reaches a constraint, we modify condition (11) to be

$$\|s(\alpha)\|_2 \leq (1+\gamma)\Delta \text{ and } \|s(\alpha)\|_\infty \geq 1. \tag{12}$$

This change does not affect the convergence of the trust region algorithm, since if $s(\alpha)$ satisfies $\|s(\alpha)\|_2 \geq \Delta(1-\beta)$ then $\|s(\alpha)\|_2 > \Delta/(1+\beta)$ and so, by our choice of Δ, $\|s(\alpha)\|_\infty \geq 1$ is automatically satisfied.

The other modification we make involves the choice of $\hat{z}$. In order to guarantee convergence, the trust region algorithm requires that the estimate $\hat{z}$ approach a singular vector of $(A_F + \alpha I)$ as $\alpha \to -\lambda_1$. To compute $\hat{z}$, it applies a Linpack [8] type condition estimator to the matrix $(A_F + \alpha I)$. However, for our algorithms, we also need $\hat{z}$ to be a direction of nonpositive curvature. We ensure this as follows. When we attempt to compute the Cholesky factorization of A_F and it breaks down, we compute a direction of nonpositive curvature as in Section 2.1. We normalize this vector and call it $\hat{y}$. Note that $\hat{y}$ and has the property that

$$0 \geq \hat{y}^T A_F \hat{y} \geq \lambda_1. \tag{13}$$

We then begin the trust region algorithm. Each time we need an approximation to $\hat{z^*}$, we compute a vector $\hat{v}$ using the trust region algorithm's condition estimator. We compare $\hat{v}$ to $\hat{y}$, and set $\hat{z}$ to be whichever of the two directions is a direction of greater negative curvature. Equation (13) and the fact that $\hat{v}$ approaches a singular vector of $(A_F + \alpha I)$ as $\alpha \to -\lambda_1$, assure us that $\hat{z}$ will always be a direction of nonpositive curvature while maintaining the condition that $\hat{z}$ approaches a singular vector as $\alpha \to -\lambda_1$.

To implement the trust region algorithm for sparse problems, we need to compute the Cholesky factorization of matrices of the form $(A_F + \alpha I)$, where $(A_F + \alpha I) > 0$. Since the sparsity structures of $(A_F + \alpha I)$ and A_F are the same, we can use the same data structure to store their Cholesky factors. Notice that as α changes, the Cholesky factor of $(A_F + \alpha I)$ changes significantly, and our updating scheme cannot be used to obtain the new factor. Thus we must recompute the entire Cholesky factor of $(A_F + \alpha I)$ each time α changes.

4.4 Finding a Starting Point

If we use the new descent direction algorithm, we do not need to start with a free set F such that A_F is positive definite. This allows us to use a preprocessing heuristic to find a starting point that quickly binds a subset of the variables, hopefully with as much accuracy as possible. Our heuristic uses global information to select which variables to bind in much the same way as our new search direction algorithm did.

We find an initial active set and a starting point as follows. Let $F := \{1, \ldots, n\}$ and $x := 0$. Repeat the following steps a finite number of times. First, find a point s which is an approximate global minimizer of q_F on a simpler region. Then find the point p in the feasible region closest to $x + Z_F s$. Let p be the starting point and compute $g(p)$. Finally, bind any variable that is at a bound and whose corresponding component of $g(p)$ has the correct sign, and update F.

When A_F is positive definite, we solve the unconstrained problem

$$\min \tfrac{1}{2}s^T A_F s + g_F^T s.$$

This amounts to setting s to be the Newton direction. However when A_F is not positive definite, this quadratic may be unbounded below. Instead we find an approximate solution to a problem

$$\begin{gathered}\min \tfrac{1}{2}s^T A_F s + g_F^T s \\ \|s\|_2 \leq \Delta\end{gathered}$$

for some appropriate Δ as described in the previous section. Using our projection operator notation, we are setting $p := \Pi(x + Z_F s)$.

To determine how many times to repeat this loop, we introduce three parameters m_1, m_2, and m_3. We terminate after we have executed the loop m_1 times, or we have bound less than m_2 variables in the past m_3 iterations.

5 Numerical Results

In what follows, we describe the implementation details of *GSA* and various modifications to *GSA* that incorporate our heuristic improvements of Section 4. We provide numerical results for a battery of test problems and use these results to suggest the algorithm which we feel to be the most useful in practice. We also briefly discuss some less successful approaches.

5.1 Implementation Details

We implemented our algorithms in Fortran in double precision and made extensive use of Sparspak [12] in our implementation. We use Sparspak's GENMMD routine to find an initial minimum degree ordering of A and SMBFCT to perform the symbolic factorization and set up the data structure for L. We modified Sparspak's Cholesky factorization routine GSFCT and triangular solve routine GSSLV to allow us to ignore any specified set of rows and columns.

To compute the search directions of Section 4.2, we modified the Fortran code GQTPAR of Moré and Sorensen [18] to handle sparse matrices. To compute the Cholesky factorization and perform forward and backward triangular solves we use the modified Sparspak routines GSFCT and GSSLV. We slightly modified Sparspak's condition estimator routines COND51 and COND52 to produce the eigenvector approximations we need.

We generated problems by using Coleman's routine [4] that, given the structure of a matrix A, generates a lower triangular matrix L with the property that $\eta(LL^T) \subseteq \eta(A)$. We then set $A = LDL^T$, where D is a diagonal matrix of plus and minus ones. We control the condition number of A by choosing the values of the diagonal of L, and determine the number of negative eigenvalues of A by selecting the number of -1's on the diagonal of D.

For positive definite A, we generate the b vectors as follows. Given parameters θ and μ, we generate a feasible vector x by setting θ-percent of the x_i to a bound, and assigning the rest randomly in the open interval $(-1,1)$; we set μ-percent of the bound x_i to negative bounds. We then set $g = Ax$ and

$$b_i = \begin{cases} -g_i & \text{if } -1 < x_i < 1 \\ -g_i - v_i & \text{if } x_i = 1 \\ -g_i + v_i & \text{if } x_i = -1, \end{cases}$$

where the v_i's are random numbers in $(0,10)$. Note that since A is positive definite, x is the solution of our problem. This allows us to control the percentage of variables bound at the solution, a critical factor in the running times of these problems. For indefinite problems, we generate the b vectors by setting $b = Ax$, where the components of x are randomly chosen in $(-1,1)$. We chose this interval in an attempt to generate difficult problems.

The heuristics of Sections 4.2 – 4.4 contained the parameters γ, β, m_1, m_2, and m_3 that we left unspecified. Based on some limited testing, we feel that reasonable choices of these parameters are $\gamma = 0.9$, $\beta = 0.1$, $m_1 = 10$, $m_2 = 2$, and $m_3 = 8$.

5.2 The Algorithms

We began by implementing *GSA* and found it to be slow on positive definite problems. In particular, it spends a great deal of time for each variable it binds, especially in the beginning when the free set is large. To remedy this we incorporated the projection techniques into *GSA*. When we modified *GSA* by adding projection techniques in both the main loop of the program and in the initial stationary point loop, we found that it ran slower because we could bind many variables at a time but only free them one at a time. Thus we included projection techniques only in the initial stationary point loop and we refer to this algorithm as *PSA* (Projected Sparse Active set algorithm). *PSA* tended to run much faster than *GSA*, especially on problems that were moderately or heavily bound at the solution. This is because *GSA* is more accurate in selecting which variables to bind; *PSA* is less accurate, but it binds variables more quickly. On the problems that were moderately or heavily bound at the solution, the amount of time spent binding was more important, since a large proportion of the variables needed to be bound. On the problems that were lightly bound at the solution, binding the wrong variables took considerable time to remedy, since we are freeing them one at a time. The algorithm *PSA* shows the value of the projection techniques.

For indefinite and negative definite problems, *GSA* and *PSA* found local minima with approximately the same function value. They ran very quickly on these problems, since many of the variables were bound during the initial Cholesky factorization.

Next we modified *GSA* by using the new search direction for the indefinite case. Each time we reach a constrained stationary point, we free all of the variables whose gradients have incorrect sign, something we could not do when we used the Cholesky breakdown direction for the indefinite case. Because computation of our new direction does not update the Cholesky factorizations, computation of each direction is expensive. Thus we project each search direction to allow us to bind several variables for each direction we compute. Since the direction is an approximation to the minimum of q_F on an ellipse centered at the current point, we call the algorithms that use the new search direction

Table 1: The Features of the Algorithms

method	heuristic starting pt	initial stationary pt.		main loop	
		neg curv dirn	projecting	neg curv dirn	projecting
GSA	no	breakdown	no	breakdown	no
PSA	no	breakdown	yes	breakdown	no
PEA	no	new	yes	new	yes
PEAS	yes	new	yes	new	yes
PEGAS	yes	new	yes	breakdown	no

Ellipse Active set algorithms. The algorithm with these improvements *PEA* (Projected Ellipse Active set algorithm) ran much faster than *PSA* on positive definite problems. On indefinite problems, *PEA* found local minima that were lower than those found by *GSA* or *PSA*. The running time of *PEA* on indefinite problems was considerably longer than *PSA*, since *PEA* uses global information. However, the running time of *PEA* on indefinite problems was comparable to the running time of *PEA* on positive definite problems with the same structure and size. The algorithm *PEA* highlights the value of our new search direction and of freeing many variables at a time.

Next we incorporated the starting point heuristic into *PEA*. We call the resulting algorithm *PEAS*. (Projected Ellipse Active set algorithm with Starting point heuristic) *PEAS* ran much faster than *PEA* on positive definite problems. The running time of *PEAS* on indefinite problems was faster than *PEA*, and *PEAS* found local minima that were lower than those found by *PEA*. The algorithm *PEAS* shows the value of our starting point heuristic.

Finally, we implemented an algorithm *PEGAS* (Projected Ellipse General Active set algorithm with Starting point heuristic) that was identical to *PEAS* until it found an initial stationary point and was identical to *GSA* after that. *PEGAS* ran faster than *PEAS* on positive definite problems, ran marginally slower on indefinite problems, and found local minima with almost identical function values as those found by *PEAS*. This seems to indicate that once a good stationary point is found, switching back to the *GSA* algorithm with its efficient Cholesky factor updating and its adding and dropping of one constraint at each iteration works best.

In Table 1, we tabulate the features of the algorithms we have just described. We refer to the direction used by *GSA* for nonpositive definite problems as *breakdown*, since we compute it from the Cholesky factorization when it breaks down.

We need to consider the convergence of these algorithms. In Sections 4.1 – 4.2 we saw that for each direction we follow, we bind at least one variable, and if we take a step of nonzero length, we decrease the function value. These facts, together with the arguments used to show convergence of *GSA*, ensure the convergence of the algorithms in Table 1 to a point satisfying (3) with $A_F > 0$ in a finite number of iterations.

5.3 Results

We ran our double precision Fortran algorithms on a Sun 3/50 under UNIX 4.2 Release 3.5 with the parameters described in Section 5.1. We tested our algorithms on positive definite and indefinite problems. We chose three approximate condition number ranges: 10^3 – 10^5, 10^8 – 10^{10}, and 10^{13} – 10^{15}. (Note that machine epsilon is about 10^{-19}.) To approximate the condition number κ of each problem, we used Higham's Condest routine [16]. To solve the systems required by Condest, we used Gilbert and Peierls *LU* factorization code [13]. We used three sparsity structures from Everstine [9]: the problem of size 503 with 6027 nonzeroes, the problem of size 1005 with 8621 nonzeroes, and the problem of size 2680 with 25026 nonzeroes. The tables referred to in this section are in the appendix, along with Table 1, which describes the algorithms.

For positive definite problems, we chose three values of θ, the percentage of variables bound at the solution: 10, 50, and 90. For each of the 9 different combinations of κ and θ, we generated four different quadratics, yielding a total of 36 problems for each sparsity pattern. For each condition number range, Table 2 lists the sum of the running times in seconds of the 12 problems with that range; for each percentage of variables bound at the solution, Table 3 lists the sum of the running times in seconds of the 12 problems with that percentage of variables bound. As we stated in Section 5.2, *PEGAS* runs the fastest on these problems, with *PEAS* slightly slower. The other algorithms are several times slower.

For indefinite problems, we chose three values for the percentage of eigenvalues of A that were negative: 10, 50, and 90. For each of the 9 different combinations of κ and the percentage of negative eigenvalues, we generated four different quadratics, yielding a total of 36 problems for each sparsity pattern. To compare running times, for each percentage of negative eigenvalues, Table 4 shows the sum of the running times in seconds of the 12 problems with that percentage. The ellipse algorithms display much less sensitivity to the percentage of negative eigenvalues than *GSA* or *PSA*, although the latter are considerably faster on problems with a high percentage of negative eigenvalues. To compare the local minima found, for each percentage of negative eigenvalues, Table 5 displays the normalized sum of the function values at the local minimum found in the 12 problems with that percentage. Also, for each condition number range, Table 6 displays the normalized sum of the function values at the local minimum found in the 12 problems with that range. We normalize the sum of the function values with the formula

$$\text{normalized total value} = \frac{\text{lowest total value}}{\text{total value}},$$

so that the lowest function value is normalized to 1, and the others are normalized to values greater than 1. Of the five algorithms, *PEGAS* and *PEAS* find the lowest minima, with *PEA* slightly higher.

Tables 7 – 11 show the approximate percentage of time spent performing the major tasks of each algorithm for two problem sizes, 503 and 1005, on 6 representative problems. All six problems have condition numbers in the range 10^8 – 10^{10}. Three are positive definite, with 10, 50, and 90 percent of the variables bound at the solution; three are indefinite, with 10, 50, and 90 percent of the eigenvalues negative. The tables divide the algorithm up into two or three main parts: the starting point heuristic (if appropriate), the initial constrained stationary point loop, and the main loop of the program. They tabulate separately the tasks performed in each major part. Since we also set up the data structure, permute the matrix, and compute an initial factorization (if appropriate), the percentage of time spent in these three tasks does not add up to 100. Most of the tasks listed are self explanatory, but a few merit further clarification. In Table 8, the task *project* includes computing α and updating g and L_F. In Tables 9 – 11, the task *solve* consists of solving for the Newton direction or the ellipse direction, as appropriate, and the task *project* includes updating g.

In general, *GSA* spends most of its time in the initial stationary point loop. Solving for the search direction and updating the gradient within this loop are its most time consuming tasks. Compared to *GSA*, *PSA* spends more of its time in the main loop. Its most time consuming tasks are projecting the search direction in the initial stationary point loop and solving for the search direction and updating the gradient in the main loop. Except for lightly bound positive definite problems, *PEA* spends most of its time computing the initial stationary point. For positive definite problems, factoring the matrix and projecting the search direction in both loops are its most time consuming tasks; for indefinite problems, solving for and projecting the search direction in the initial stationary point loop are its most time consuming tasks. The algorithms *PEAS* and *PEGAS* spend most of their time computing the starting point. Notice, however, that the starting point heuristic sometimes finds an initial stationary point and even an optimal point. For these algorithms, the starting point heuristic spends most of its time factoring in positive definite problems, and solving for the search direction in indefinite problems.

Tables 12 – 13 shows the average number of search directions computed for the problems of size 503. The ellipse algorithms tend to compute fewer search directions than either *GSA* or *PSA*.

Table 14 shows the average percentage of variables bound at the solution for the indefinite problems of size 503. For each group of problems, all of the algorithms tend to find local minima with approximately the same percentage of variables bound at the solution.

Tables 15 – 16 display the average number of variables freed for the problems of size 503. In the algorithms that use the starting point heuristic, all variables that the heuristic sets to a bound are counted as bound; those whose corresponding component of the gradient have the incorrect sign are then counted as freed. We do not include the number of variables bound, since for positive definite problems, it is just a constant plus the number of variables freed, and for indefinite problems, Table 14 shows that it is almost a constant plus the number of variables freed. Thus the number of variables freed is a good measure of how well the algorithms choose which variables to bind and free. For positive definite problems, notice that *GSA* frees many fewer variables than the other algorithms, and that in almost all cases, the problems with higher condition numbers have more variables freed. For indefinite problems, the ellipse algorithms tend to free fewer variables, especially those algorithms with the starting point heuristic.

5.4 Other Possibilities

There are obviously many ways to combine the improvements of Section 4 into *GSA*. Some behaved similarly to the algorithms we presented so we did not tabulate results for them. In particular, when we used our starting point heuristic, projecting the search directions did not substantially affect the running times or local minima found. Other combinations performed very poorly, e.g., using our new search direction without projecting the search directions and without the starting point heuristic. Some other ideas we tried briefly that did not seem to work well include starting *GSA* at the vertex nearest (in the infinity norm sense) to the global minimum of the unconstrained quadratic and freeing variables after every iteration for the first few iterations of *PEA*.

We also tried other ways of using trust region ideas in our algorithm that were less successful in practice. Above we solved a trust region problem to find the search direction when A_F was not positive definite. We also tried solving a trust region problem to find the search direction when A_F was positive definite and the Newton step was not feasible. We implemented two different versions: one where we used this technique for finding a search direction only when we were finding a starting point and initial stationary point, and another where we used this technique for finding all search directions. The former was more successful but neither method worked as well as the ones that used the Newton step.

6 Conclusion

We showed that direct active set methods that solve both definite and indefinite quadratic programs with simple bounds can be efficiently implemented for large sparse problems. All of the necessary factorizations can be carried out in a static data structure requiring space equal to that needed for a single Cholesky factorization of A. We can efficiently update the Cholesky factorization of A_F if we are only binding or freeing one variable at a time.

We showed that our new descent direction for the indefinite case and our new heuristic method for finding a starting point, combined with projection techniques, produced an algorithm that runs much faster than the basic algorithm for positive definite problems and finds local minima with lower function values for indefinite and negative definite problems.

There may be ways we can improve our algorithm. For example, we could use a line search procedure along the piecewise quadratic $P(x + \alpha s)$ instead of exactly computing the first local minimum, or incorporate projected gradients into an algorithm using our new descent direction algorithm and/or our new heuristic starting point algorithm.

Our results may have some applications in solving the least squares problem

$$\begin{aligned} &\min \tfrac{1}{2}x^T C^T C x + d^T x \\ &l \leq x \leq u. \end{aligned} \tag{14}$$

As we mentioned in Section 1, Björck [2] proposed an algorithm for solving (14) that is very similar to *GSA*. Our improvements could be added to such an algorithm. However, computing and updating the Cholesky factorization is more complicated in the least squares case; in particular, since we do not wish to compute $A^T A$, adding a row and column to L_F cannot be accomplished stably with a single triangular solve. All of the algorithms we propose vary the active set more than *GSA* does. Thus the time saved by our improvements may not be as great in the least squares case, and there may be tradeoffs in stability.

Our results show that minimizing a quadratic with simple bounds may be very expensive compared to minimizing the quadratic subject to a two-norm bound on the solution, since we solve several two-norm problems in our fastest algorithm. This suggests that for large sparse problems, minimizing a quadratic with simple bounds as a subproblem of a more difficult problem, e.g., minimizing a nonlinear function subject to simple bounds, may not be very practical.

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Appendix

Table 1: The Features of the Algorithms

method	heuristic starting pt	initial stationary pt.		main loop	
		neg curv dirn	projecting	neg curv dirn	projecting
GSA	no	breakdown	no	breakdown	no
PSA	no	breakdown	yes	breakdown	no
PEA	no	new	yes	new	yes
PEAS	yes	new	yes	new	yes
PEGAS	yes	new	yes	breakdown	no

Table 2: Running Times (secs) vs. Condition Number for Positive Definite Problems

n	κ	*GSA*	*PSA*	*PEA*	*PEAS*	*PEGAS*
503	$10^3 - 10^5$	1522.54	688.02	312.06	158.34	138.88
	$10^8 - 10^{10}$	1666.50	739.24	440.54	192.66	161.54
	$10^{13} - 10^{15}$	1699.78	760.36	528.92	218.76	181.90
	total	4888.82	2187.62	1281.52	569.76	482.32
1005	$10^3 - 10^5$	*	1999.68	1085.96	559.64	473.66
	$10^8 - 10^{10}$	*	2049.50	1480.64	560.86	491.40
	$10^{13} - 10^{15}$	*	2159.48	1956.78	623.48	525.54
	total	*	6208.66	4523.38	1743.98	1490.60
2680	$10^3 - 10^5$	*	*	3690.46	912.86	769.70
	$10^8 - 10^{10}$	*	*	4649.44	979.24	854.26
	$10^{13} - 10^{15}$	*	*	5478.60	1213.66	944.40
	total	*	*	13818.50	3105.76	2568.36

* requires excessive CPU time

Table 3: Running Times (secs) vs. Percent of Variables Bound for Positive Definite Problems

n	% bnd	*GSA*	*PSA*	*PEA*	*PEAS*	*PEGAS*
503	10	1530.12	1222.38	701.38	371.22	288.44
	50	1675.80	605.34	320.66	118.56	115.10
	90	1682.90	359.90	259.48	79.98	78.78
	total	4888.82	2187.62	1281.52	569.76	482.32
1005	10	*	3409.14	2290.84	1058.52	832.48
	50	*	1795.04	1159.60	410.50	384.26
	90	*	1004.48	1072.94	271.20	273.86
	total	*	6208.66	4523.38	1743.98	1490.60
2680	10	*	*	5747.06	1976.96	1520.40
	50	*	*	4349.32	677.74	611.02
	90	*	*	3722.12	451.06	436.94
	total	*	*	13818.50	3105.76	2568.36

* requires excessive CPU time

Table 4: Running Times (secs) vs. Percentage of Negative Eigenvalues for Indefinite Problems

n	% neg ev	*GSA*	*PSA*	*PEA*	*PEAS*	*PEGAS*
503	10	630.76	193.76	194.54	178.94	180.14
	50	128.68	62.86	192.52	166.76	166.42
	90	33.46	34.38	179.80	154.78	155.56
	total	792.90	291.00	566.86	500.48	502.12
1005	10	2652.46	529.66	613.12	523.36	544.98
	50	469.96	167.22	643.90	503.34	532.56
	90	91.88	89.38	650.50	461.04	475.60
	total	3214.30	786.26	1907.52	1487.74	1553.14
2680	10	*	3004.82	2711.46	1099.54	1294.56
	50	2978.92	734.04	3054.84	1092.96	1164.40
	90	271.78	242.22	3007.52	873.78	850.88
	total	*	3981.08	8773.82	3066.28	3309.84

* requires excessive CPU time

Table 5: Normalized Function Value vs. Condition Number for Indefinite Problems

n	κ	*GSA*	*PSA*	*PEA*	*PEAS*	*PEGAS*
503	$10^3 - 10^5$	1.039	1.039	1.016	1.000	1.000
	$10^8 - 10^{10}$	1.030	1.030	1.015	1.000	1.000
	$10^{13} - 10^{15}$	1.030	1.030	1.013	1.000	1.000
1005	$10^3 - 10^5$	1.022	1.022	1.008	1.000	1.000
	$10^8 - 10^{10}$	1.017	1.017	1.005	1.000	1.000
	$10^{13} - 10^{15}$	1.017	1.016	1.005	1.000	1.000
2680	$10^3 - 10^5$	*	1.025	1.011	1.000	1.000
	$10^8 - 10^{10}$	*	1.013	1.007	1.000	1.000
	$10^{13} - 10^{15}$	*	1.013	1.007	1.000	1.000

* requires excessive CPU time

Table 6: Normalized Function Value vs. Percentage of Negative Eigenvalues for Indefinite Problems

n	% neg ev	*GSA*	*PSA*	*PEA*	*PEAS*	*PEGAS*
503	10	1.002	1.002	1.000	1.000	1.000
	50	1.030	1.030	1.010	1.000	1.000
	90	1.052	1.052	1.026	1.000	1.000
1005	10	1.002	1.002	1.000	1.000	1.000
	50	1.012	1.011	1.004	1.000	1.000
	90	1.035	1.035	1.011	1.000	1.000
2680	10	*	1.001	1.000	1.000	1.000
	50	1.004	1.004	1.003	1.000	1.000
	90	1.037	1.037	1.018	1.000	1.000

* requires excessive CPU time

Table 7: Percentage of Time Spent Performing Subtasks in *GSA*

		Positive Definite						Indefinite					
		503			1005			503			1005		
		% bnd			% bnd			% neg ev			% neg ev		
		10	50	90	10	50	90	10	50	90	10	50	90
init stat pt	solve	34	45	51	47	58	62	36	22	2	54	34	3
	update g	15	23	26	13	19	21	35	26	1	27	30	5
	update L_F	8	11	12	4	6	6	3	3	1	3	1	2
	total	61	85	96	69	89	96	84	61	8	93	77	14
main loop	solve	13	3	0	13	3	0	2	2	1	0	1	0
	update g	6	3	0	4	2	0	3	4	1	0	1	0
	update L_F	13	3	0	8	2	0	1	1	0	0	0	0
	total	35	11	1	27	8	1	8	13	10	2	4	3

Table 8: Percentage of Time Spent Performing Subtasks in *PSA*

		Positive Definite						Indefinite					
		503			1005			503			1005		
		% bnd			% bnd			% neg ev			% neg ev		
		10	50	90	10	50	90	10	50	90	10	50	90
init stat pt	solve	2	2	4	1	1	4	2	1	0	2	1	0
	project	20	41	68	17	33	57	25	18	6	36	21	5
	total	21	43	72	18	34	60	27	19	6	37	21	5
main loop	solve	23	11	1	33	16	1	8	6	1	6	2	0
	update g	15	15	2	16	16	2	19	8	1	8	5	1
	update L_F	26	9	1	18	7	1	7	3	0	3	2	0
	total	75	49	14	76	55	21	50	32	11	38	25	5

Table 9: Percentage of Time Spent Performing Subtasks in *PEA*

		Positive Definite						Indefinite					
		503			1005			503			1005		
		% bnd			% bnd			% neg ev			% neg ev		
		10	50	90	10	50	90	10	50	90	10	50	90
init stat pt	solve	3	4	6	1	2	4	30	24	43	31	28	27
	factor	21	30	46	15	32	51	2	1	0	1	0	0
	project	10	29	32	12	32	31	52	52	42	57	60	64
	total	34	64	84	29	67	86	84	76	86	89	88	91
main loop	solve	8	4	0	5	3	0	1	2	0	1	0	0
	factor	49	16	1	58	16	2	3	1	0	0	0	0
	project	7	10	7	5	10	7	2	13	6	1	3	1
	total	63	30	9	69	28	9	6	15	7	2	4	1

Table 10: Percentage of Time Spent Performing Subtasks in *PEAS*

		Positive Definite						Indefinite					
		503			1005			503			1005		
		% bnd			% bnd			% neg ev			% neg ev		
		10	50	90	10	50	90	10	50	90	10	50	90
start pt	solve	5	8	9	4	7	6	75	74	77	83	84	80
	factor	37	53	56	52	64	70	4	2	1	2	1	1
	project	3	8	12	2	4	6	10	12	10	4	5	7
	total	46	71	79	58	75	82	89	89	89	90	91	88
init stat pt	solve	2	0	0	1	0	0	0	0	0	0	0	0
	factor	13	0	0	11	0	0	0	0	0	0	0	0
	project	1	0	0	0	0	0	0	0	2	0	0	1
	total	16	0	0	12	0	0	0	0	2	0	0	1
main loop	solve	4	3	0	2	1	0	0	0	0	0	0	0
	factor	28	11	0	22	10	0	0	0	0	0	0	0
	project	2	3	0	1	1	0	0	0	0	0	0	0
	total	34	16	0	24	13	0	0	0	0	0	0	0

Table 11: Percentage of Time Spent Performing Subtasks in *PEGAS*

		Positive Definite						Indefinite					
		503			1005			503			1005		
		% bnd			% bnd			% neg ev			% neg ev		
		10	50	90	10	50	90	10	50	90	10	50	90
start pt	solve	7	9	8	6	7	6	75	74	77	82	84	80
	factor	51	54	56	67	72	70	4	2	1	2	1	1
	project	5	9	12	2	5	5	10	12	10	4	5	6
	total	63	73	78	75	85	82	89	89	89	89	91	88
init stat pt	solve	3	0	0	1	0	0	0	0	0	0	0	0
	factor	18	0	0	14	0	0	0	0	0	0	0	0
	project	2	0	0	0	0	0	0	0	2	0	0	1
	total	22	0	0	15	0	0	0	0	2	0	0	1
main loop	solve	34	4	0	2	1	0	0	0	0	0	0	0
	update g	1	3	0	0	0	0	0	0	0	0	0	0
	update L_F	5	4	0	1	0	0	0	0	0	0	0	0
	total	10	13	0	3	2	0	0	0	0	0	0	0

Table 12: Average Number of Search Directions Computed for Positive Definite Problems

	% bnd	κ: $10^3 - 10^5$	$10^8 - 10^{10}$	$10^{13} - 10^{15}$
GSA	10	211.25	308.00	333.00
	50	359.75	428.00	436.75
	90	475.75	496.25	496.25
PSA	10	330.75	353.25	372.75
	50	280.00	326.75	302.00
	90	181.75	191.50	178.75
PEA	10	16.75	15.25	27.50
	50	14.00	13.25	18.50
	90	25.00	27.50	14.75
PEAS	10	8.50	11.25	14.00
	50	6.00	7.25	6.50
	90	4.75	5.25	5.00
PEGAS	10	14.50	16.75	20.75
	50	6.50	10.25	8.25
	90	4.75	5.00	5.00

Table 13: Average Number of Search Directions Computed for Indefinite Problems

		κ		
	% bnd	$10^3 - 10^5$	$10^8 - 10^{10}$	$10^{13} - 10^{15}$
GSA	10	307.50	317.50	320.50
	50	185.75	174.75	168.00
	90	43.00	37.75	36.50
PSA	10	171.50	158.00	148.50
	50	81.75	72.25	67.25
	90	22.00	20.00	18.25
PEA	10	10.25	9.25	9.25
	50	12.75	11.75	11.25
	90	7.25	8.00	6.25
PEAS	10	10.25	9.00	10.25
	50	14.50	13.00	11.00
	90	12.50	12.50	11.25
PEGAS	10	10.25	9.00	34.00
	50	39.25	24.25	11.00
	90	13.00	12.75	11.25

Table 14: Average Percent of Variables Bound at the Solution for Indefinite Problems

	% neg ev	κ: $10^3 - 10^5$	$10^8 - 10^{10}$	$10^{13} - 10^{15}$
GSA	10	73.43	79.75	81.45
	50	92.65	94.85	95.00
	90	99.45	99.65	99.65
PSA	10	73.43	79.75	81.45
	50	92.70	94.85	95.10
	90	99.45	99.65	99.65
PEA	10	73.53	79.80	81.55
	50	92.25	94.85	95.00
	90	99.50	99.70	99.55
PEAS	10	73.73	79.80	81.40
	50	92.50	94.85	95.25
	90	99.50	99.75	99.60
PEGAS	10	73.73	79.80	81.40
	50	92.50	94.85	95.25
	90	99.50	99.75	99.60

Table 15: Average Number of Variables Freed for Positive Definite Problems

		κ		
	% bnd	$10^3 - 10^5$	$10^8 - 10^{10}$	$10^{13} - 10^{15}$
GSA	10	89.00	141.75	156.00
	50	62.50	101.00	105.25
	90	17.50	33.00	33.75
PSA	10	325.00	345.25	363.25
	50	275.50	320.75	292.75
	90	177.25	185.00	170.25
PEA	10	329.50	363.75	390.00
	50	319.25	399.75	354.00
	90	213.50	227.25	202.50
PEAS	10	487.25	637.50	708.50
	50	433.00	544.00	553.75
	90	264.75	324.50	337.00
PEGAS	10	486.75	637.25	708.50
	50	433.00	544.00	553.75
	90	264.75	324.50	337.00

Table 16: Average Number of Variables Freed for Indefinite Problems

	% neg ev	κ: $10^3 - 10^5$	$10^8 - 10^{10}$	$10^{13} - 10^{15}$
GSA	10	49.25	48.75	39.50
	50	44.25	39.00	34.00
	90	18.00	17.75	15.75
PSA	10	164.25	150.25	142.25
	50	70.50	60.75	57.25
	90	18.50	18.00	16.00
PEA	10	27.75	20.75	20.50
	50	52.25	34.75	34.25
	90	13.00	11.75	8.75
PEAS	10	6.25	6.75	38.50
	50	33.50	14.75	1.50
	90	0.75	1.25	0.25
PEGAS	10	6.25	6.75	32.75
	50	29.50	13.25	1.50
	90	0.75	1.25	0.25

References

[1] Dimitri P. Bertsekas. Projected Newton methods for optimization problems with simple constraints. *SIAM Journal on Control and Optimization*, 20(2):221–246, 1982.

[2] Åke Björck. A direct method for sparse least squares problems with lower and upper bounds. Technical report, Linköping University, 1986.

[3] Paul H. Calamai and Jorge J. Moré. Projected gradient methods for linearly constrained problems. *Mathematical Programming*, 39:93–116, 1987.

[4] Thomas F. Coleman. A chordal preconditioner for large scale optimization. *Mathematical Programming*, 40:265–287, 1988.

[5] A. R. Conn, N. I. M. Gould, and Ph. L. Toint. Global convergence of a class of trust region algorithms for optimization with simple bounds. *SIAM Journal on Numerical Analysis*, 25(2):433–460, 1988.

[6] A. R. Conn, N. I. M. Gould, and Ph. L. Toint. Testing a class of methods for solving minimization problems with simple bounds on the variables. *Mathematics of Computation*, 50(182):399–430, 1988.

[7] Ron S. Dembo and Ulrich Tulowitzki. On the minimization of quadratic functions subject to box constraints. Technical Report B 71, Yale University, 1983.

[8] J. J. Dongarra, J. R. Bunch, C. B. Moler, and G. W. Stewart. *LINPACK Users' Guide.* SIAM Publications, 1979.

[9] G. C. Everstine. A comparison of three resequencing algorithms for the reduction of matrix profile and wave front. *International Journal for Numerical Methods in Engineering*, 14:837–853, 1979.

[10] R. Fletcher. A general quadratic programming algorithm. *Journal of the Institute of Mathematics and its Applications*, 7:76–91, 1971.

[11] R. Fletcher and M. P. Jackson. Minimization of a quadratic function of many variables subject only to lower and upper bounds. *Journal of the Institute of Mathematics and its Applications*, 14:159–174, 1974.

[12] Alan George and Joseph W. H. Liu. *Computer Solution of Large Sparse Positive Definite Systems.* Prentice-Hall, 1981.

[13] John R. Gilbert and Timothy Peierls. Sparse partial pivoting in time proportional to arithmetic operations. Technical Report 86–783, Cornell University, 1986. To appear in *SIAM Journal on Scientific and Statistical Computing.*

[14] Philip E. Gill and Walter Murray. Numerically stable method for quadratic programming. *Mathematical Programming*, 14:349–372, 1978.

[15] Philip E. Gill, Walter Murray, and Margaret H. Wright. *Practical Optimization*. Academic Press, 1981.

[16] N. J. Higham. Fortran codes for extimating the one-norm of a real or complex matrix, with applications to condition extimation. Technical Report Numerical Analysis Report No. 135, University of Manchester, 1987.

[17] Jorge J. Moré. Numerical solution of bound constrained problems. Technical Report 96, Argonne National Laboratory, 1987.

[18] Jorge J. Moré and D. C. Sorensen. Computing a trust region step. *SIAM Journal on Scientific and Statistical Computing*, pages 553–572, 1983.

[19] Katta G. Murty and Santosh N. Kabadi. Some NP-complete problems in quadratic and nonlinear programming. *Mathematical Programming*, 39:117–129, 1987.

[20] Donald J. Rose, Robert Endre Tarjan, and George S. Lueker. Algorithmic aspects of vertex elimination on graphs. *SIAM Journal on Computing*, 5:266–283, 1976.

[21] Mihalis Yannakakis. Computing the minimum fill-in is NP-complete. *SIAM Journal on Algebraic and Discrete Methods*, 2:77–79, 1981.

[22] Yinyu Ye and Edison Tse. A polynomial-time algorithm for convex quadratic programming. Technical report, Stanford University, 1986.