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# An interior-point trust-funnel algorithm for nonlinear optimization using a squared-violation feasibility measure

Frank E. Curtis,<sup>1,2</sup> Nicholas I. M. Gould,<sup>3,3</sup> and Daniel P. Robinson<sup>5,6</sup> and Philippe L. Toint<sup>7</sup>

## ABSTRACT

We present an interior-point trust-funnel algorithm for solving large-scale nonlinear optimization problems. The method is based on an approach proposed by Gould and Toint (*Math. Prog.*, 122(1):155-196, 2010) that focused on solving equality constrained problems. Our method, which is designed to solve problems with both equality and inequality constraints, achieves global convergence guarantees by combining a trust-region methodology with a funnel mechanism. The prominent features of our algorithm are that (i) the subproblems that define each search direction may be solved approximately, (ii) criticality measures for feasibility and optimality aid in determining which subset of computations will be performed during each iteration, (iii) no merit function or filter is used, (iv) inexact sequential quadratic optimization steps may be computed when advantageous, and (v) it may be implemented matrix-free so that derivative matrices need not be formed or factorized so long as matrix-vector products with them can be performed. This variant uses the square of the violation as a feasibility measure.

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## 0 Preamble

In [6], we described a new interior-point trust-funnel algorithm for nonlinear optimization in which inequality constraints  $c(x) \leq 0$  were converted to equations  $c(x) + s = 0$  by the addition of slack variables  $s \geq 0$ . The infeasibility of iterates was measured by the violation  $\|c(x) + s\|_2$  for which  $s > 0$  was ensured by the mechanics of the algorithm.

The algorithm in [6] was derived from the one proposed in [26] that focused on problems involving equality-constraints. In [26], the infeasibility of iterates was measured by the *square* of the violation. The purpose of the present paper is to analyze an algorithm for inequality constraints that follows [26] by measuring the violation by  $\|c(x) + s\|_2^2$  rather than  $\|c(x) + s\|_2$ . The algorithm itself is very similar to that in [6], the main differences being the squaring of the violation and its dominating “funnel”, and the formula for the reduction in the funnel as the iterations proceed. While there is certainly substantial overlap in the resulting convergence analysis, the details are considerably different in parts, and our intention is to describe those differences here. However, since this paper is not intended for journal publication, and for the convenience of the reader, we have chosen to include the complete motivation and analysis for the algorithm that uses squared violation, rather than merely highlighting the differences with [6].

Our intention is to compare both variants in our forthcoming implementation and numerical tests.

## 1 Introduction

In this paper, we introduce a method for solving optimization problems of the form

$$\underset{x \in \mathbb{R}^N}{\text{minimize}} \quad f(x) \quad \text{subject to} \quad c(x) \leq 0, \quad (\text{NP})$$

where  $f : \mathbb{R}^N \rightarrow \mathbb{R}$  and  $c : \mathbb{R}^N \rightarrow \mathbb{R}^M$  are twice continuously differentiable. (Our method can also be applied when equality constraints are present, but, for simplicity in our discussion, they are suppressed in our algorithm development and analysis; see §5 for further discussion.) Our algorithm is designed to solve large-scale instances of (NP). In particular, it is designed to be matrix-free in the sense that it can be implemented while only requiring matrix-vector products with the constraint Jacobian, its transpose, symmetric approximations of the Hessian of the Lagrangian, and corresponding preconditioners. Thus, iterative methods may be used for approximately solving each subproblem arising in the algorithm.

The method we propose utilizes components of both interior-point (IP) and sequential quadratic optimization (commonly known as SQP) methods. Algorithms of this type are often referred to as barrier-SQP methods. The interior-point aspects of our algorithm allow us to avoid the combinatorial explosion that may occur within, say, an active-set approach. The efficiency of interior-point methods for solving linear and convex quadratic programming problems has been well-established [1, 8, 13–15, 19, 20, 27, 31, 33]. Extending these methods for solving nonlinear problems has been the subject of research for decades [3, 4, 7, 16, 34–38] and numerical evidence illustrates strong performance. We follow an approach similar to Byrd et. al. [3, 4] and solve a sequence of so-called barrier subproblems for decreasing values of the barrier parameter. This means that we must solve a sequence of equality constrained subproblems, and these may be solved very efficiently with an SQP method. It is well known that traditional SQP methods are very efficient for solving small- to medium-sized optimization problems [9, 10, 17, 18], while more recently proposed SQP methods utilize exact second derivatives and are, in theory, capable of solving large problems [22–24, 32]. Preliminary results when solving small- to medium-sized problems is promising, but their effectiveness on large problems has not yet been confirmed. There have, however, been several proposed SQP strategies that have proved capable of solving large *equality* constrained problems [2, 26, 30].

In this paper we use the trust-funnel approach originally described in [26], and then corrected in [25], as the basis for solving a sequence of equality constrained barrier subproblems that arise in an interior-

point framework. We note, however, that a naïve implementation of the SQP method described in [25,26] within an interior-point paradigm may result in a method for which the establishment of convergence guarantees is elusive. This is a consequence of the fact that interior-point methods—as their name suggests—require the algorithm iterates to remain in the strict interior of the feasible region associated with the inequality constraints, while the method in [25,26] does not innately possess the mechanisms necessary to avoid the boundary of the feasible region in this context. In this paper, we describe modifications of this trust-funnel method that are appropriate for our interior-point setting. These modifications include imposing explicit constraints in the trust-region subproblems to ensure that the iterates remain in the strict interior of the feasible region, and the incorporation of scaled trust-region constraints and optimality measures. Scalings of these types have been used previously in interior-point methods; e.g., see [3,7].

The paper is organized as follows. In Section 2 we introduce our trust-funnel algorithm for solving the barrier subproblem in an interior-point approach. In Section 3 we prove that our trust-funnel algorithm will terminate finitely with arbitrarily small positive tolerances on the criticality measures. In Section 4 we consider convergence of the barrier subproblem solutions for a decreasing sequence of the barrier parameter. Finally, conclusions are provided in Section 5.

## Notation

The gradient and Hessian of  $f$  at  $x$  are written as  $g(x)$  and  $\nabla_{xx}f(x)$  respectively. The  $M \times N$  matrix  $J(x)$  represents the Jacobian of the constraint function  $c$  evaluated at  $x$ , with its  $j$ th row being  $\nabla c_j(x)^T$ . The matrix  $\nabla_{xx}c_j(x)$  is the Hessian of  $c_j$  evaluated at  $x$ . We let  $e$  denote the vector of all ones and  $I$  denote the identity matrix, both of whose dimensions are determined by the context in which they are used. Given a vector  $s \in \mathbb{R}^M$ ,  $[s]_j$  is the  $j$ th element of  $s$  and  $S := \text{diag}([s]_1, [s]_2, \dots, [s]_M)$ . A forcing function  $\omega : [0, \infty) \rightarrow [0, \infty)$  is defined as any continuous and strictly increasing function that satisfies  $\omega(0) = 0$ .

## Preliminaries

We make the following assumption throughout the paper.

**Assumption 1.1.** *The functions  $f$  and  $c$  are twice continuously differentiable.*

Problem (NP) is not solved directly by our algorithm. Rather, we introduce a vector of slack variables  $s \in \mathbb{R}^M$  and solve the equivalent problem

$$\underset{x \in \mathbb{R}^N, s \in \mathbb{R}^M}{\text{minimize}} \quad f(x) \quad \text{subject to} \quad c(x, s) := c(x) + s = 0, \quad s \geq 0. \quad (\text{NPs})$$

The following definition gives first-order stationarity conditions for (NPs) [28,29].

**Definition 1.1** (First-order KKT point for problem (NPs)). *The vector triple  $(x, s, y)$  is a first-order KKT point for problem (NPs) if it satisfies*

$$g(x) + J(x)^T y = 0, \quad c(x, s) = 0, \quad S y = 0, \quad \text{and} \quad (s, y) \geq 0.$$

To solve (NPs), we compute a sequence of (approximate) minimizers of the barrier subproblem

$$\underset{x \in \mathbb{R}^N, s \in \mathbb{R}^M}{\text{minimize}} \quad f(x, s) \quad \text{subject to} \quad c(x, s) = 0, \quad s > 0, \quad (1.1)$$

where for each fixed value of  $\mu > 0$  we define the barrier function

$$f(x, s) := f(x) - \mu \sum_{i=1}^M \ln([s]_i). \quad (1.2)$$

Given a Lagrange multiplier estimate vector  $y$  for the constraint  $c(x, s) = 0$ , the Lagrangian function associated with (1.1) and its gradient with respect to  $(x, s)$  are given by

$$\mathcal{L}(x, s, y) := f(x, s) + c(x, s)^T y \quad \text{and} \quad \nabla_{(x,s)} \mathcal{L}(x, s, y) := \nabla f(x, s) + J(x, s)^T y,$$

where we define  $J(x, s) := \nabla c(x, s) = (J(x) \ I)$  to represent the Jacobian of  $c(x, s)$  with respect to  $(x, s)$ . A primal-dual point  $(x, s, y)$  is called a first-order KKT point of the barrier problem (1.1) if it satisfies

$$\nabla_{(x,s)} \mathcal{L}(x, s, y) = 0, \quad c(x, s) = 0, \quad \text{and} \quad (s, y) > 0.$$

Multiplying the second block of the first equation by  $S$  leads to the following equivalent definition.

**Definition 1.2** (First-order KKT point for the barrier subproblem (1.1)). *The vector triple  $(x, s, y)$  is a first-order KKT-point for the barrier subproblem (1.1) if it satisfies*

$$g(x) + J(x)^T y = 0, \quad S y = \mu e, \quad c(x, s) = 0, \quad \text{and} \quad (s, y) > 0.$$

A comparison of Definitions 1.1 and 1.2 suggests that KKT points of the barrier subproblem become increasingly accurate solutions to problem (NPs) for decreasing values of the barrier parameter  $\mu$ .

## 2 A Trust-Funnel Algorithm for Solving the Barrier Subproblem

In this section, we present our trust-funnel algorithm for (approximately) solving the barrier subproblem (1.1) for a fixed value of the barrier parameter  $\mu > 0$ . As  $\mu$  is fixed for a particular instance of (1.1), the dependence on  $\mu$  of certain quantities in this section is ignored. However, these dependences—in particular, with respect to criticality tolerances that are employed in the algorithm—will be a central focus in §4 that addresses the “outer” algorithm for solving problem (NPs).

### 2.1 Algorithm overview

Our method generates a sequence  $\{(x_k, s_k, y_k)\}$  of primal, slack, and dual variables. Moreover, defining the measure of equality constraint violation

$$v(x, s) := \|c(x, s)\|_2^2, \tag{2.1}$$

our method maintains a monotonically decreasing sequence of positive scalars  $\{v_k^{\max}\}$  that satisfy

$$s_k > 0, \quad c(x_k, s_k) \geq 0, \quad v_k := v(x_k, s_k) \leq v_k^{\max}, \quad \text{and} \quad v_{k+1}^{\max} \leq v_k^{\max} \quad \text{for all } k \geq 0. \tag{2.2}$$

We require  $s_0 > 0$ , and the restriction  $s_k > 0$  is maintained via explicit constraints imposed on all search direction calculations. Additionally, we ensure that  $c(x_k, s_k) \geq 0$  is satisfied at the beginning of iteration  $k$  by incorporating a *slack reset* procedure defined by

$$[s_k]_i \leftarrow \begin{cases} [s_k]_i & \text{if } [c(x_k, s_k)]_i \geq 0, \\ -[c(x_k)]_i & \text{otherwise.} \end{cases} \tag{2.3}$$

If we let  $s_k^{\text{prior}}$  denote the value of  $s_k$  prior to the slack reset in iteration  $k$ , then it follows that

$$v_k \leq v(x_k, s_k^{\text{prior}}), \quad s_k^{\text{prior}} \leq s_k, \quad \text{and} \quad f(x_k, s_k) \leq f(x_k, s_k^{\text{prior}}). \tag{2.4}$$

Therefore, both the barrier function and constraint violation have decreased as the result of the trivial slack reset computation (2.3). We explicitly enforce  $v_k \leq v_k^{\max}$  with the updating strategy discussed in

Section 2.4. Finally, the sequence  $\{v_k^{\max}\}$  is positive and monotonically decreasing by construction and guides the iterates toward feasibility; the set of infeasible points permitted by the gradually narrowing region defined by  $v(x, s) \leq v_k^{\max}$  is what we call the *funnel*. Overall, all claims in (2.2) are formally established in Section 2.6.

Given the current estimate  $(x_k, s_k)$  of a solution, a trial step  $d_k := (d_k^x, d_k^s)$  is computed as the sum of a “normal” step  $n_k := (n_k^x, n_k^s)$  and a “tangential” step  $t_k := (t_k^x, t_k^s)$ , i.e.,

$$d_k = \begin{pmatrix} d_k^x \\ d_k^s \end{pmatrix} = \begin{pmatrix} n_k^x \\ n_k^s \end{pmatrix} + \begin{pmatrix} t_k^x \\ t_k^s \end{pmatrix} = n_k + t_k.$$

The normal step is computed to (approximately) minimize a quadratic model of  $v$  at  $(x_k, s_k)$ ; thus, it has the purpose of reducing linearized infeasibility. The tangential step  $t_k$  is intended to reduce the barrier function (1.2) and is calculated as an (approximate) minimizer of a quadratic model of the barrier function within an appropriate subspace that does not undo the improvement in reducing linearized infeasibility achieved by  $n_k$ . Once  $d_k = n_k + t_k$  is computed, an attempt to decrease the constraint violation and/or barrier function is made, where the decision to do so is based on quantities that reflect the overall merit of the constituent steps. We discuss these details in turn in the following subsections.

## 2.2 The normal step

The normal step is designed to predict a reduction in the constraint violation as measured by  $v$  defined in (2.1). To achieve this goal, we compute the normal step  $n_k := (n_k^x, n_k^s)$  as an approximate solution of

$$\underset{n=(n^x, n^s)}{\text{minimize}} \quad m_k^v(n) \quad \text{subject to} \quad \|P_k^{-1}n\|_2 \leq \min\{\delta_k^v, \kappa_n \pi_k^v\}, \quad s_k + n^s \geq \kappa_{\text{fbn}} s_k, \quad (2.5)$$

where we define

$$m_k^v(n) := \|c(x_k, s_k) + J(x_k, s_k)n\|_2^2, \quad P_k := \begin{pmatrix} I & 0 \\ 0 & S_k \end{pmatrix}, \quad (2.6)$$

and the  $v$ -criticality measure

$$\pi_k^v := \pi^v(x_k, s_k) := \|P_k J(x_k, s_k)^T c(x_k, s_k)\|_2, \quad (2.7)$$

where  $\delta_k^v > 0$  is updated dynamically by the algorithm, and where  $\kappa_n \geq 1$  and  $\kappa_{\text{fbn}} \in (0, 1)$  are constants. It will be shown in Lemma 3.14 that  $\pi_k^v$  is a criticality measure at  $(x_k, s_k)$  for minimizing  $v$  subject to the slacks being nonnegative. The scaling matrix  $P_k$  is important in the trust region constraint since it assists in keeping iterates within the nonnegative orthant; it restricts  $[n_k^s]_j$  to be relatively small when  $[s_k]_j$  is close to zero. Problem (2.5) involves the local minimization of the norm of a Gauss-Newton approximation of  $v$  at  $(x_k, s_k)$  subject to a trust-region constraint and fraction-to-the-boundary rule.

It is not necessarily prudent to compute a normal step every iteration. Indeed, computing a normal step may be wasteful if the current iterate is nearly feasible and computational efforts may be better spent on computing a new Lagrange multiplier estimate or tangential step. In our algorithm, we only require a normal step to be computed when either our  $v$ -criticality measure  $\pi_k^v$  is significant in comparison to the previous  $f$ -criticality measure  $\pi_{k-1}^f$  associated with minimizing the barrier function (the definition of  $\pi_k^f$  is given by (2.23) in the next subsection), or when  $v_k$  is not sufficiently small compared to the upper bound  $v_k^{\max}$  (see (2.2)). Specifically, for some constant  $\kappa_{\text{vv}} \in (0, 1)$  and forcing function  $\omega_n$  (and with  $\pi_{-1}^f := 0$ ), we require the computation of a normal step if either

$$\pi_k^v > \omega_n(\pi_{k-1}^f) \quad \text{or} \quad v_k \geq \kappa_{\text{vv}} v_k^{\max}. \quad (2.8)$$

(If (2.8) does not hold, but  $\pi_k^v > 0$ , one may consider computing a normal step since the fact that

$\pi_k^v > 0$  implies that the computation would be well-defined. However, a normal step is not necessary for our convergence analysis in this case.) When a normal step is not computed, we simply set  $n_k \leftarrow 0$ .

By an approximate solution to (2.5), we mean that  $n_k := (n_k^x, n_k^s)$ —when it is computed—should be feasible for (2.5) and it should yield a decrease in  $m_k^v$  no less than that achieved along a scaled steepest descent direction. In particular, the scaled steepest descent direction that we employ is derived in the following manner. If we perform the change of variables  $n^P := P_k^{-1}n$  so that the trust-region constraint becomes  $\|n^P\|_2 \leq \min\{\delta_k^v, \kappa_n \pi_k^v\}$ , then the transformed problem has the conventional Euclidean norm steepest descent direction  $-P_k J(x_k, s_k)^T c(x_k, s_k)$ . Returning to the original space gives the scaled steepest descent direction  $-P_k^2 J(x_k, s_k)^T c(x_k, s_k)$ . For (2.5), we define the Cauchy step  $n_k^C = (n_k^{Cx}, n_k^{Cs})$  as the minimizer of the objective of (2.5) in the scaled steepest descent direction, i.e.,

$$n_k^C := n_k^C(\alpha_N^C), \quad \text{where } n_k^C(\alpha) := \begin{pmatrix} n_k^{Cx}(\alpha) \\ n_k^{Cs}(\alpha) \end{pmatrix} := -\alpha P_k^2 J(x_k, s_k)^T c(x_k, s_k) \quad (2.9)$$

and  $\alpha_N^C$  is the solution to

$$\underset{\alpha \geq 0}{\text{minimize}} \quad m_k^v(n_k^C(\alpha)) \quad \text{subject to} \quad \|P_k^{-1}n_k^C(\alpha)\|_2 \leq \min\{\delta_k^v, \kappa_n \pi_k^v\}, \quad s_k + n_k^{Cs}(\alpha) \geq \kappa_{\text{fbn}} s_k. \quad (2.10)$$

We show in Lemma 2.8 that the decrease in  $m_k^v$  obtained by  $n_k^C$  is positive (when  $\delta_k^v > 0$  and  $\pi_k^v > 0$ ).

Overall, when (2.8) holds, we require a normal step  $n_k$  satisfying the constraints of (2.5), i.e.,

$$\|P_k^{-1}n_k\|_2 \leq \min\{\delta_k^v, \kappa_n \pi_k^v\}, \quad s_k + n_k^s \geq \kappa_{\text{fbn}} s_k, \quad (2.11)$$

along with

$$\Delta m_k^{v,n} := m_k^v(0) - m_k^v(n_k) \geq m_k^v(0) - m_k^v(n_k^C). \quad (2.12)$$

Many steps satisfy (2.11) and (2.12) with the simplest choice being  $n_k = n_k^C$ .

### 2.3 Lagrange multipliers and the tangential step

Having dealt with the normal step, we now consider computing estimates of an optimal Lagrange multiplier vector and/or a tangential step. If computed, the multiplier estimates are intended to (approximately) minimize a measure of criticality for the barrier subproblem (1.1) that takes into account changes in the problem function values that are predicted by the normal step. Likewise, the tangential step, if computed, is designed to reduce the barrier function without having too adverse an effect on the reduction in linearized infeasibility predicted by the normal step. Since the conditions imposed on the multiplier estimates and tangential step are intimately related—e.g., the computed multiplier estimates are required to lead to a well-defined Cauchy point for the tangential step subproblem—we consider their computation together in this section. Our motivation in this section is to compute quantities related to those in a traditional SQP approach applied to subproblem (1.1).

Given the  $k$ th estimate  $y_k$  of an optimal Lagrange multiplier vector, a traditional SQP trial step associated with the barrier subproblem (1.1) is defined as the solution (when it exists) of

$$\underset{d=(d^x, d^s)}{\text{minimize}} \quad f(x_k, s_k) + \nabla f(x_k, s_k)^T d + \frac{1}{2} d^T \nabla_{(x,s)(x,s)} \mathcal{L}(x_k, s_k, y_k) d \quad \text{subject to} \quad c(x_k, s_k) + J(x_k, s_k) d = 0.$$

It may be verified that a solution  $d = (d^x, d^s)$  of this subproblem (when it exists) satisfies

$$\begin{pmatrix} \nabla_{xx} \mathcal{L}(x_k, y_k) & J(x_k)^T & 0 \\ J(x_k) & 0 & I \\ 0 & S_k & \mu S_k^{-1} \end{pmatrix} \begin{pmatrix} d^x \\ y \\ d^s \end{pmatrix} = - \begin{pmatrix} g(x_k) \\ c(x_k, s_k) \\ -\mu e \end{pmatrix}, \quad (2.13)$$

where  $y$  is an estimate of an optimal Lagrange multiplier vector for the constraint  $c(x_k, s_k) + J(x_k, s_k) d =$

0. The SQP step generated in this fashion is often called a *primal* step since the dual vector  $y_k$  does not appear in (2.13) other than in the Hessian  $\nabla_{xx}\mathcal{L}$ . We can instead compute a *primal-dual* step by applying Newton's Method to the conditions in Definition 1.2, which leads to

$$\begin{pmatrix} \nabla_{xx}\mathcal{L}(x_k, y_k) & J(x_k)^T & 0 \\ J(x_k) & 0 & I \\ 0 & S_k & Y_k \end{pmatrix} \begin{pmatrix} d^x \\ y \\ d^s \end{pmatrix} = - \begin{pmatrix} g(x_k) \\ c(x_k, s_k) \\ -\mu e \end{pmatrix}. \quad (2.14)$$

This system is identical to (2.13), except that the (3,3)-block now contains dual information. It is also easily verified that a solution of (2.14) is a KKT point for

$$\underset{d=(d^x, d^s)}{\text{minimize}} \quad f(x_k, s_k) + \nabla f(x_k, s_k)^T d + \frac{1}{2} d^T H(x_k, s_k, y_k) d \quad \text{subject to} \quad c(x_k, s_k) + J(x_k, s_k) d = 0,$$

where

$$H(x_k, s_k, y_k) := \begin{pmatrix} \nabla_{xx}\mathcal{L}(x_k, y_k) & 0 \\ 0 & Y_k S_k^{-1} \end{pmatrix}.$$

The previous paragraph, along with the widely accepted view that the *primal-dual* approach is generally superior to the *primal* approach in practice, motivates us to approximate the barrier function (1.2) with

$$m_k^f(d) := f(x_k, s_k) + \nabla f(x_k, s_k)^T d + \frac{1}{2} d^T G_k d, \quad (2.15)$$

where we define

$$G_k := \begin{pmatrix} \nabla_{xx}\mathcal{L}(x_k, y_k^B) & 0 \\ 0 & D_k \end{pmatrix}, \quad (2.16)$$

let  $y_k^B$  be a (bounded) Lagrange multiplier vector satisfying

$$[y_k^B]_i > 0 \quad \text{for all } i \in \{1, 2, \dots, M\} \quad \text{and} \quad \|y_k^B\|_2 \leq \kappa_y \quad \text{for some scalar } \kappa_y > 0, \quad (2.17)$$

and choose  $D_k \approx Y_k S_k^{-1}$  as a positive-definite diagonal matrix satisfying

$$\|D_k\|_2 \leq \kappa_D \quad \text{for all } k \geq 0 \quad \text{and some scalar } \kappa_D > 0. \quad (2.18)$$

Overall, our goal is to compute a tangential step  $t_k$  that satisfies  $m_k^f(n_k + t_k) \leq m_k^f(n_k)$  and lies approximately in the null space of the constraint Jacobian  $J(x_k, s_k)$  so as not to undo the predicted gain in linearized feasibility provided by the normal step. This latter requirement implies that improvement in the barrier function should be sought within the trust-region  $\{d : \|P_k^{-1}d\|_2 \leq \delta_k^v\}$ , since it is only within this region that the linearized constraint model is believed to be trustworthy. In addition, we assume that the barrier function model  $m_k^f$  may be trusted as a faithful representation within the trust-region  $\{d : \|P_k^{-1}d\|_2 \leq \delta_k^f\}$  for a given tangential trust-region radius  $\delta_k^f > 0$ . Consequently, we use

$$\|P_k^{-1}n_k\|_2 \leq \kappa_B \min\{\delta_k^v, \delta_k^f\} \quad \text{with } \kappa_B \in (0, 1) \quad (2.19)$$

as a necessary condition for computing a tangential step. If (2.19) is satisfied, we require the computation of a new Lagrange multiplier estimate and, potentially, a tangential step. Otherwise, we set  $y_k \leftarrow y_{k-1}$  and  $t_k \leftarrow 0$  since the cost of computing new multipliers and a tangential step may be wasteful.

When (2.19) is satisfied, we seek an approximate solution of the tangential step subproblem

$$\begin{aligned} & \underset{t=(t^x, t^s)}{\text{minimize}} \quad m_k^f(n_k + t) \\ & \text{subject to} \quad J(x_k, s_k)t = 0, \quad \|P_k^{-1}(n_k + t)\|_2 \leq \min\{\delta_k^v, \delta_k^f\}, \quad s_k + n_k^s + t^s \geq \kappa_{\text{rbt}}(s_k + n_k^s) \end{aligned} \quad (2.20)$$

for some  $\kappa_{\text{rbt}} \in (0, 1)$ . Observing the change of variables  $t^P = P_k^{-1}t$ , this subproblem is equivalent to

$$\begin{aligned} & \underset{t^P=(t^{P_x}, t^{P_s})}{\text{minimize}} && m_k^f(n_k + P_k t^P) \\ & \text{subject to} && J(x_k, s_k)P_k t^P = 0, \quad \|P_k^{-1}n_k + t^P\|_2 \leq \min\{\delta_k^v, \delta_k^f\}, \quad t^{P_s} \geq (\kappa_{\text{rbt}} - 1)(e + S_k^{-1}n_k^s). \end{aligned}$$

To define an appropriate Cauchy point, we first compute approximate least-squares multipliers corresponding to the scaled subproblem at  $t^P = 0$ , i.e., we compute  $y_k$  as an approximate solution of

$$\underset{y \in \mathbb{R}^M}{\text{minimize}} \quad m_k^{\mathcal{L}}(y), \quad \text{where} \quad m_k^{\mathcal{L}}(y) := \frac{1}{2} \|P_k(\nabla m_k^f(n_k) + J(x_k, s_k)^T y)\|_2^2. \quad (2.21)$$

Scaling the resulting (approximate) projected gradient back into the original space, we obtain the (approximate) oblique projected gradient

$$r_k := r_k(y_k), \quad \text{where} \quad r_k(y) := P_k^2 \left( \nabla m_k^f(n_k) + J(x_k, s_k)^T y \right), \quad (2.22)$$

and the related  $f$ -criticality measures

$$\pi_k^f := \pi_k^f(y_k), \quad \text{where} \quad \pi_k^f(y) := \|P_k(\nabla m_k^f(n_k) + J(x_k, s_k)^T y)\|_2, \quad (2.23)$$

and

$$\chi_k^f := \chi_k^f(y_k) \equiv \frac{\nabla m_k^f(n_k)^T r_k}{\pi_k^f}, \quad \text{where} \quad \chi_k^f(y) := \frac{\nabla m_k^f(n_k)^T r_k(y)}{\pi_k^f(y)}, \quad (2.24)$$

associated with minimizing the barrier function. In this computation, we require that  $y_k$  and the resulting  $r_k$ ,  $\pi_k^f$ , and  $\chi_k^f$  satisfy at least one of the following three sets of conditions:

$$\pi_k^f \leq \epsilon_\pi \quad \text{and} \quad v_k \leq \epsilon_v; \quad (2.25a)$$

$$\pi_k^f \leq \omega_t(\pi_k^v); \quad (2.25b)$$

$$\chi_k^f \geq \kappa_\chi \pi_k^f. \quad (2.25c)$$

Here,  $\{\epsilon_\pi, \epsilon_v\} > 0$  and  $\{\kappa_\chi, \kappa_{\text{nr}}\} \subset (0, 1)$  are constants and  $\omega_t$  is a forcing function. For technical reasons (in the proof of Lemma 2.6(vii)), we require the functions  $\omega_n$  and  $\omega_t$  (see (2.8) and (2.25b)) satisfy

$$\omega_t(\omega_n(\tau)) \leq \kappa_\omega \tau \quad \text{for all } \tau \geq 0 \quad \text{and for some } \kappa_\omega \in (0, 1). \quad (2.26)$$

The presence of  $P_k$  in (2.21) forces components of the approximate projected gradient in (2.22) to be large when the corresponding components of  $s_k$  are small. Thus the scaling matrix helps prevent slack variables from approaching zero, just as it did in the formulation of the normal step subproblem (2.5). Lemma 2.10 shows that we can always satisfy one of the three sets of conditions in (2.25), and thus this strategy for computing  $y_k$  (and the related quantities  $r_k$ ,  $\pi_k^f$ , and  $\chi_k^f$ ) is well-posed.

If (2.25a) is satisfied, then  $(x_k, s_k, y_k)$  is an approximate first-order KKT point for the barrier subproblem for the tolerances  $\{\epsilon_\pi, \epsilon_v\} > 0$ , so we terminate the algorithm. However, if (2.25a) is not satisfied, but (2.25b) holds, then the  $f$ -criticality measure  $\pi_k^f$  is insubstantial compared to the  $v$ -criticality measure  $\pi_k^v$ . In this case, the computation of a tangential step is skipped, i.e., we simply set  $t_k \leftarrow 0$ . Otherwise, when (2.25a) and (2.25b) do not hold (and necessarily (2.25c) holds), we proceed to compute a tangential step. In this case, it follows from the definition (2.24), the condition (2.25c) and the fact that  $\pi_k^f > 0$  (since otherwise (2.25b) would have held) that  $r_k$  is a direction of strict ascent for  $m_k^f(\cdot)$  at  $n_k$ . This property allows us to compute a tangential step  $t_k$  satisfying one of two sets of conditions as outlined in the following two subsections. Our choice of which set of conditions to satisfy depends on whether a normal step is computed or not. Specifically, if  $n_k \neq 0$ , then we require the computation of what we call a relaxed SQP tangential step. Otherwise, if  $n_k = 0$ , we are still free to

attempt to compute a relaxed SQP tangential step, but we may instead compute what we call a very relaxed SQP tangential step. In such a case, this latter option may be preferable as it involves a weaker restriction on linearized infeasibility of the step.

### 2.3.1 A relaxed SQP tangential step

Given constants  $\kappa_{\text{fbt}} \in (0, 1)$  and  $\kappa_{\text{tg}}$ , a relaxed SQP tangential step is defined as follows.

**Definition 2.1** (Relaxed SQP tangential step). *Define the Cauchy point*

$$t_k^{\text{C}} := t_k^{\text{C}}(\alpha_{\text{T}}^{\text{C}}), \quad \text{where} \quad t_k^{\text{C}}(\alpha) := \begin{pmatrix} t_k^{\text{Cx}}(\alpha) \\ t_k^{\text{Cs}}(\alpha) \end{pmatrix} := -\alpha \begin{pmatrix} r_k^{\text{x}} \\ r_k^{\text{s}} \end{pmatrix} = -\alpha r_k \quad (2.27)$$

and  $\alpha_{\text{T}}^{\text{C}}$  is the minimizer of

$$\begin{aligned} & \underset{\alpha \geq 0}{\text{minimize}} && m_k^{\text{f}}(n_k + t_k^{\text{C}}(\alpha)) \\ & \text{subject to} && \|P_k^{-1}(n_k + t_k^{\text{C}}(\alpha))\|_2 \leq \min\{\delta_k^{\text{v}}, \delta_k^{\text{f}}\}, \quad s_k + n_k^{\text{s}} + t_k^{\text{Cs}}(\alpha) \geq \kappa_{\text{fbt}}(s_k + n_k^{\text{s}}). \end{aligned} \quad (2.28)$$

Then,  $t_k$  is a relaxed SQP tangential step if

$$\Delta m_k^{\text{f},t} := m_k^{\text{f}}(n_k) - m_k^{\text{f}}(n_k + t_k) \geq m_k^{\text{f}}(n_k) - m_k^{\text{f}}(n_k + t_k^{\text{C}}), \quad (2.29\text{a})$$

$$s_k + n_k^{\text{s}} + t_k^{\text{s}} \geq \kappa_{\text{fbt}}(s_k + n_k^{\text{s}}), \quad (2.29\text{b})$$

$$\|P_k^{-1}(n_k + t_k)\|_2 \leq \min\{\delta_k^{\text{v}}, \delta_k^{\text{f}}\}, \quad \text{and} \quad (2.29\text{c})$$

$$m_k^{\text{v}}(n_k + t_k) \leq \kappa_{\text{tg}} m_k^{\text{v}}(0) + (1 - \kappa_{\text{tg}}) m_k^{\text{v}}(n_k). \quad (2.29\text{d})$$

Condition (2.29a) ensures that the model of the barrier function is decreased at least as much as by the Cauchy point  $t_k^{\text{C}}$ , (2.29b) is a fraction-to-the-boundary constraint, (2.29c) is a trust-region constraint, while (2.29d) is a relaxation of the traditional SQP constraint that  $c(x_k, s_k) + J(x_k, s_k)(n_k + t_k) = 0$  and ensures that the linearized constraint-infeasibility contracts.

If a relaxed SQP tangential step satisfying (2.29) is computed, we must evaluate its usefulness in the sense that we must ensure that a relatively large tangential step results in a sufficient decrease in the model  $m_k^{\text{f}}$  of the barrier function. With this in mind, we check whether the conditions

$$\|P_k^{-1}t_k\|_2 > \kappa_{\text{vs}} \|P_k^{-1}n_k\|_2 \quad \text{for some } \kappa_{\text{vs}} > 1 \quad (2.30)$$

and

$$\Delta m_k^{\text{f},d} := \Delta m_k^{\text{f},n} + \Delta m_k^{\text{f},t} \geq \kappa_{\delta} \Delta m_k^{\text{f},t} \quad \text{for some } \kappa_{\delta} \in (0, 1) \quad \text{with } \Delta m_k^{\text{f},n} := m_k^{\text{f}}(0) - m_k^{\text{f}}(n_k) \quad (2.31)$$

are satisfied. The inequality (2.31) indicates that the predicted decrease in the barrier function obtained from the tangential step is substantial when compared to the possible increase resulting from the normal step. If the step  $t_k$  satisfies (2.30) but violates (2.31), it does not serve its role so we reset it to zero.

### 2.3.2 A very relaxed SQP tangential step

Condition (2.29) may be too restrictive in certain cases. Specifically, if  $v_k = 0$ , then the algorithm will set  $n_k = 0$ , from which it follows that (2.29d) requires  $t_k$  to be in the null space of  $J(x_k, s_k)$ . This is an unreasonable requirement in matrix-free settings; indeed (2.29d) may be unreasonable in any situation when  $n_k = 0$ . Thus, to avoid such a requirement, we allow for the computation of an alternative tangential step. Given the constant  $\kappa_{\text{fbt}} \in (0, 1)$  employed in (2.29b), and constants  $\kappa_{\text{v}} > 1$  and  $\kappa_{\text{tt}} \in (\kappa_{\text{vv}}, 1)$  (with  $\kappa_{\text{vv}} \in (0, 1)$  defined for (2.8)), the salient feature of our alternative is that it involves a relaxed condition on the linearized infeasibility of the step. We emphasize that we are only allowed to compute a tangential step of this type when  $n_k = 0$ .

**Definition 2.2** (Very relaxed SQP tangential step). *Define the Cauchy point*

$$t_k^c = t_k^c(\alpha_T^c), \quad \text{where} \quad t_k^c(\alpha) := \begin{pmatrix} t_k^{cx}(\alpha) \\ t_k^{cs}(\alpha) \end{pmatrix} := -\alpha \begin{pmatrix} r_k^x \\ r_k^s \end{pmatrix} = -\alpha r_k \quad (2.32)$$

and  $\alpha_T^c$  is the minimizer of

$$\begin{aligned} & \underset{\alpha \geq 0}{\text{minimize}} && m_k^f(n_k + t_k^c(\alpha)) \\ & \text{subject to} && \|P_k^{-1}(n_k + t_k^c(\alpha))\|_2 \leq \min\{\delta_k^v, \delta_k^f, \sqrt{\kappa_v v_k^{\max}}\}, \quad s_k + n_k^s + t_k^{cs}(\alpha) \geq \kappa_{\text{fvt}}(s_k + n_k^s). \end{aligned} \quad (2.33)$$

Then,  $t_k$  is a very relaxed SQP tangential step if

$$\Delta m_k^{f,t} := m_k^f(n_k) - m_k^f(n_k + t_k) \geq m_k^f(n_k) - m_k^f(n_k + t_k^c), \quad (2.34a)$$

$$s_k + n_k^s + t_k^s \geq \kappa_{\text{fvt}}(s_k + n_k^s), \quad (2.34b)$$

$$\|P_k^{-1}(n_k + t_k)\|_2 \leq \min\{\delta_k^v, \delta_k^f, \sqrt{\kappa_v v_k^{\max}}\}, \quad \text{and} \quad (2.34c)$$

$$m_k^v(n_k + t_k) \leq \kappa_{\text{tt}} v_k^{\max}. \quad (2.34d)$$

Conditions (2.34a)–(2.34c) resemble and play the same role as conditions (2.29a)–(2.29c). However, we emphasize that since the Cauchy point defined by (2.32)–(2.33) involves a potentially smaller trust-region radius than that defined in (2.28), the bound imposed in (2.34a) may be different from that imposed in (2.29a), and this difference in the trust-region radii is matched in (2.34c) (c.f., (2.29c)). The name “very relaxed SQP tangential step” has been chosen because of condition (2.34d), that merely requires that the predicted constraint violation be sufficiently less than a fraction of the upper bound  $v_k^{\max}$  rather than a fraction of the current violation (c.f., (2.29d)). In fact, the smaller trust-region radii in (2.33) and (2.34c) (as compared to those in (2.28) and (2.29c)) have been chosen to compensate for this relaxation.

## 2.4 Iteration type, step acceptance, and updating strategy

As in other trust-region methods, once we have computed the trial step  $d_k := n_k + t_k$  and the trial point

$$(x_k^+, s_k^+) := (x_k, s_k) + d_k,$$

we are left with the task of accepting or rejecting them. Our proposal for making this choice is based on the distinction between *y-iterations*, *f-iterations* and *v-iterations* in the spirit of [10–12]. This characterization is made based on model values computed with the trial step, and the type of iteration influences the updates performed for various algorithmic quantities.

### 2.4.1 A *y*-iteration

A *y*-iteration is any satisfying the following definition.

**Definition 2.3** (*y*-iteration). *The  $k$ th iteration is a *y*-iteration if  $d_k = 0$ .*

Note that a *y*-iteration will occur when  $n_k$  and  $t_k$  are both set to zero, but might also occur if each component is nonzero, but they sum to zero. In either case, during a *y*-iteration, we perform the updates

$$(x_{k+1}, s_{k+1}) \leftarrow (x_k, s_k), \quad \delta_{k+1}^f \leftarrow \delta_k^f, \quad \delta_{k+1}^v \leftarrow \delta_k^v, \quad \text{and} \quad v_{k+1}^{\max} \leftarrow v_k^{\max}. \quad (2.35)$$

Since a *y*-iteration is defined by a zero trial step, the only computation of interest is that of a new vector of Lagrange multiplier estimates. Therefore, the updates in (2.35) leaves the trust-region radii and bound on the maximum allowed infeasibility unchanged for the subsequent iteration.

### 2.4.2 An $f$ -iteration

The primary goal of an  $f$ -iteration is to reduce the barrier function.

**Definition 2.4** ( $f$ -iteration). *The  $k$ th iteration is an  $f$ -iteration if  $t_k \neq 0$ , (2.31) holds, and*

$$v(x_k^+, s_k^+) \leq v_k^{\max}. \quad (2.36)$$

Condition (2.36) ensures that, at the trial point  $(x_k^+, s_k^+)$ , the constraint violation remains within the upper bound imposed by  $v_k^{\max}$ . Combining this with the fact that (2.31) holds for relaxed and very relaxed SQP tangential steps, it follows that the main achievement is a predicted decrease in the value of the barrier function (1.2).

Our updating strategy for  $f$ -iterations is based on the quantity

$$\rho_k^f := \frac{f(x_k, s_k) - f(x_k^+, s_k^+)}{\Delta m_k^{f,d}}, \quad (2.37)$$

that measures the ratio of actual-to-predicted decrease in the barrier function. Specifically, if  $\rho_k^f \geq \eta_1$ , we set

$$(x_{k+1}, s_{k+1}) \leftarrow (x_k^+, s_k^+) \quad (2.38)$$

$$[s_{k+1}]_i \leftarrow \begin{cases} [s_{k+1}]_i & \text{if } [c(x_{k+1}, s_{k+1})]_i \geq 0, \\ -[c(x_{k+1})]_i & \text{otherwise,} \end{cases} \quad (2.39)$$

$$\delta_{k+1}^f \begin{cases} \in [\delta_k^f, \infty) & \text{if } \rho_k^f \geq \eta_2, \\ \in [\gamma_2 \delta_k^f, \delta_k^f] & \text{otherwise,} \end{cases} \quad (2.40)$$

$$\delta_{k+1}^v \geq \max\{\kappa_{\delta^v} \pi^v(x_{k+1}, s_{k+1}), \delta_k^v\} \quad (2.41)$$

Otherwise (i.e., if  $\rho_k^f < \eta_1$ ), we set

$$(x_{k+1}, s_{k+1}) \leftarrow (x_k, s_k), \quad (2.42)$$

$$\delta_{k+1}^f \in [\gamma_1 \delta_k^f, \gamma_2 \delta_k^f], \quad (2.43)$$

$$\delta_{k+1}^v \leftarrow \delta_k^v. \quad (2.44)$$

In both cases, we set

$$v_{k+1}^{\max} \leftarrow v_k^{\max}. \quad (2.45)$$

In (2.38)–(2.45), the constants should be chosen to satisfy  $0 < \eta_1 \leq \eta_2 < 1$ ,  $0 < \gamma_1 \leq \gamma_2 < 1$ , and  $\kappa_{\delta^v} > 0$ . In this scenario, we accept the trial point  $(x_k^+, s_k^+)$  if the achieved decrease in the barrier function is comparable to the predicted decrease, and reject it otherwise. The radius  $\delta_{k+1}^f$  is set by (2.40), represents a typical trust-region updating strategy. In addition, the value of the normal step trust-region radius is possibly increased, and the infeasibility limit is left unchanged since the success or failure of an  $f$ -iteration depends only on whether the barrier function was substantially reduced.

### 2.4.3 A $v$ -iteration

When the conditions that define a  $y$ - and an  $f$ -iteration are not satisfied, the iteration type defaults to that of a  $v$ -iteration. As we shall see in the convergence analysis of our algorithm, the focus of such an iteration is a reduction in constraint violation.

**Definition 2.5** (*v*-iteration). *The  $k$ th iteration is a  $v$ -iteration if it is not a  $y$ - or an  $f$ -iteration, i.e., if  $d_k \neq 0$  and either  $t_k = 0$ , (2.31) does not hold, or (2.36) does not hold.*

A measure of decrease one might expect in  $v$  from the trial step  $d_k$  is

$$\Delta m_k^{v,d} := m_k^v(0) - m_k^v(d_k). \quad (2.46)$$

Consequently, our updating strategy in a  $v$ -iteration is based on the conditions

$$n_k \neq 0 \quad \text{and} \quad \Delta m_k^{v,d} \geq \kappa_{\text{cd}} \Delta m_k^{v,n} \quad (2.47)$$

for some constant  $\kappa_{\text{cd}} \in (0, 1 - \kappa_{\text{tg}}] \subset (0, 1)$  with  $\kappa_{\text{tg}}$  defined in (2.29d), and the quantity

$$\rho_k^v := \frac{v_k - v(x_k^+, s_k^+)}{\Delta m_k^{v,d}}, \quad (2.48)$$

that measures the ratio of actual-to-predicted decrease in the constraint violation. Using these conditions and quantities, if (2.47) holds and  $\rho_k^v \geq \eta_1$ , we set

$$(x_{k+1}, s_{k+1}) \leftarrow (x_k^+, s_k^+) \quad (2.49)$$

$$[s_{k+1}]_i \leftarrow \begin{cases} [s_{k+1}]_i & \text{if } [c(x_{k+1}, s_{k+1})]_i \geq 0, \\ -[c(x_{k+1})]_i & \text{otherwise,} \end{cases} \quad (2.50)$$

$$\delta_{k+1}^v \begin{cases} \geq \max\{\kappa_{\delta vv} \pi^v(x_{k+1}, s_{k+1}), \delta_k^v\} & \text{if } \rho_k^v \geq \eta_2, \\ = \max\{\kappa_{\delta vv} \pi^v(x_{k+1}, s_{k+1}), \delta_k^v\} & \text{otherwise,} \end{cases} \quad (2.51)$$

$$v_{k+1}^{\max} \leftarrow \max\{\kappa_{t1} v_k^{\max}, v(x_{k+1}, s_{k+1}) + \kappa_{t2}(v_k - v(x_{k+1}, s_{k+1}))\}. \quad (2.52)$$

Otherwise (i.e., if (2.47) does not hold or  $\rho_k^v < \eta_1$ ), we set

$$(x_{k+1}, s_{k+1}) \leftarrow (x_k, s_k), \quad (2.53)$$

$$\delta_{k+1}^v \in [\gamma_1 \delta_k^v, \gamma_2 \delta_k^v], \quad (2.54)$$

$$v_{k+1}^{\max} \leftarrow v_k^{\max}. \quad (2.55)$$

In both cases, we set

$$\delta_{k+1}^f \leftarrow \delta_k^f. \quad (2.56)$$

In (2.49)–(2.56), the constants should be chosen to satisfy  $\{\kappa_{t1}, \kappa_{t2}\} \subset (0, 1)$  and  $\kappa_{\delta vv}$  defined in (2.41). In this manner, the trial point is accepted if the normal step is nonzero and the improvement in linearized feasibility is comparable to its predicted value, which is itself comparable to the improvement yielded by the normal step. The radius  $\delta_{k+1}^v$  is set by a standard trust-region radius updating strategy, but the radius  $\delta_{k+1}^f$  is left unchanged. Finally, we decrease the upper bound  $v_k^{\max}$  when the trial step is accepted. It will be shown in our convergence analysis that the amount that this bound is decreased is nontrivial, but it is modest enough so that the funnel does not contract too quickly.

## 2.5 The trust-funnel algorithm

We formally state our trust-funnel method as Algorithm 1 on page 14. For convenience in our convergence analysis, we define several sets that classify each iteration, as well as the types of computations

**Algorithm 1** Trust-funnel algorithm for minimizing the barrier problem (1.1).

- 
- 1: **Input:**  $(x_0, s_0, y_{-1}, \mu)$  and  $(\epsilon_\pi, \epsilon_v)$  with  $(s_0, y_{-1}, \mu) > 0$  and  $(\epsilon_\pi, \epsilon_v) \geq 0$ , respectively.
  - 2: Choose  $\{\delta_0^f, \delta_0^v, \kappa_{ca}, \kappa_y, \kappa_D, \kappa_{\delta vv}\} \subset (0, \infty)$ ,  $\{\kappa_{cr}, \kappa_{vs}, \kappa_v\} \subset (1, \infty)$ ,  $0 < \eta_1 \leq \eta_2 < 1$ ,  $0 < \gamma_1 \leq \gamma_2 < 1$ ,  $\kappa_n \geq 1$ ,  $\{\kappa_{tt}, \kappa_\delta, \kappa_{tg}, \kappa_\omega, \kappa_{nr}, \kappa_\chi, \kappa_B, \kappa_{vv}, \kappa_{fbb}, \kappa_{fbt}, \kappa_{t1}, \kappa_{t2}\} \subset (0, 1)$ , and  $\kappa_{cd} \in (0, 1 - \kappa_{tg}]$ .
  - 3: Perform a slack reset to  $s_0$  as given by (2.3).
  - 4: Set  $v_0^{\max} = \max[\kappa_{ca}, \kappa_{cr}v_0]$  and  $\pi_{-1}^f = 0$ .
  - 5: **for**  $k = 0, 1, \dots$  **do**
  - 6:     Compute  $\pi_k^v$  from (2.7).
  - 7:     **if**  $\pi_k^v = 0$  and  $v_k > 0$  **then**
  - 8:         Return the infeasible stationary point  $(x_k, s_k)$ .
  - 9:     **if** (2.8) holds, or at least  $\pi_k^v > 0$  **then**
  - 10:         Compute  $n_k$  satisfying (2.11) and (2.12). [ $k \in \mathcal{N}$ ]
  - 11:     **else**
  - 12:         Set  $n_k \leftarrow 0$ .
  - 13:     Compute  $\Delta m_k^{v,n}$  from (2.12).
  - 14:     Select a vector  $y_k^B$  satisfying (2.17) and define  $G_k$  by (2.16).
  - 15:     **if** (2.19) holds **then**
  - 16:         Compute  $y_k, r_k, \pi_k^f$ , and  $\chi_k^f$  from (2.21)–(2.24) to satisfy (2.25a), (2.25b), or (2.25c).
  - 17:         **if** (2.25a) holds **then**
  - 18:             Return the (approximate) first-order KKT point  $(x_k, s_k, y_k)$  for the barrier problem (1.1).
  - 19:         **else if** (2.25b) holds **then**
  - 20:             Set  $t_k \leftarrow 0$ .
  - 21:         **else**
  - 22:             **if**  $k \in \mathcal{N}$  **then**
  - 23:                 Compute  $t_k$  so that (2.29) is satisfied. [ $k \in \mathcal{T}$ ]
  - 24:             **else**
  - 25:                 Compute  $t_k$  so that either (2.29) or (2.34) is satisfied. [ $k \in \mathcal{T}$ ]
  - 26:             **if** (2.29) holds **then**
  - 27:                 Add iteration  $k$  to the set  $\mathcal{T}_D$ . [ $k \in \mathcal{T}_D$ ]
  - 28:                 **if** (2.30) is satisfied but (2.31) fails **then**
  - 29:                     Set  $t_k \leftarrow 0$ . [ $k \in \mathcal{T}_0$ ]
  - 30:         **else**
  - 31:             Set  $y_k \leftarrow y_{k-1}$  and  $t_k \leftarrow 0$ , and then set  $r_k, \pi_k^f$ , and  $\chi_k^f$  by (2.22)–(2.24).
  - 32:             **if** (2.25a) holds **then**
  - 33:                 Return the (approximate) first-order KKT point  $(x_k, s_k, y_k)$  for the barrier problem (1.1).
  - 34:         **if** (2.29d) holds **then**
  - 35:             Add iteration  $k$  to the set  $\mathcal{D}$ . [ $k \in \mathcal{D}$ ]
  - 36:         Set the trial step  $d_k \leftarrow n_k + t_k$  and trial iterate  $(x_k^+, s_k^+) \leftarrow (x_k, s_k) + d_k$ .
  - 37:         **if**  $d_k = 0$  **then**
  - 38:             Perform the  $y$ -iteration updates given by (2.35). [ $k \in \mathcal{Y}$ ]
  - 39:         **else if**  $t_k \neq 0$  and both (2.31) and (2.36) hold **then**
  - 40:             Perform the  $f$ -iteration updates given by (2.38)–(2.45). [ $k \in \mathcal{F}$ ]
  - 41:         **else**
  - 42:             Perform the  $v$ -iteration updates given by (2.49)–(2.56). [ $k \in \mathcal{V}$ ]
-

performed in them. The first group of sets distinguishes between  $y$ -,  $f$ -, and  $v$ -iterations, respectively:

$$\mathcal{Y} := \{k \in \mathbb{N} : d_k = 0\}, \quad \mathcal{F} := \{k \in \mathbb{N} : t_k \neq 0 \text{ and (2.31) and (2.36) hold}\}, \quad \text{and} \quad \mathcal{V} := \mathbb{N} \setminus (\mathcal{Y} \cup \mathcal{F}).$$

It is easy to see that these sets are mutually exclusive and exhaustive.

Our next collection of index sets distinguishes iterations for which the normal and/or tangential steps satisfy various conditions, and whether the tangential step was reset to zero:

$$\begin{aligned} \mathcal{N} &:= \{k \in \mathbb{N} : n_k \text{ was computed to satisfy (2.11) and (2.12)}\}; \\ \mathcal{T} &:= \{k \in \mathbb{N} : t_k \text{ was computed to satisfy either (2.29) or (2.34)}\}; \\ \mathcal{T}_{\mathcal{D}} &:= \{k \in \mathcal{T} : \text{the computed } t_k \text{ satisfied (2.29)}\}; \\ \mathcal{T}_0 &:= \{k \in \mathcal{T}_{\mathcal{D}} : \text{the computed } t_k \text{ satisfied (2.29) and (2.30), but not (2.31), and was reset to zero}\}. \end{aligned}$$

Furthermore the set of iterations for which  $d_k$  satisfies the linearized constraint contraction condition (2.29d) plays an important role in our analysis. Thus, in addition to the sets above, we define

$$\mathcal{D} := \{k \in \mathbb{N} : \text{the step } d_k = n_k + t_k \text{ satisfies (2.29d)}\}.$$

Our last collection of sets distinguishes iterations that produce a change in the primal space. In particular, if  $\rho_k^f \geq \eta_1$  holds during an  $f$ -iteration, or if (2.47) holds and  $\rho_k^v \geq \eta_1$  during a  $v$ -iteration, then iteration  $k$  is called *successful*. The following sets capture these types of iterations:

$$\mathcal{S}_f := \{k \in \mathcal{F} : \rho_k^f \geq \eta_1\}; \quad \mathcal{S}_v := \{k \in \mathcal{V} : (2.47) \text{ holds and } \rho_k^v \geq \eta_1\}; \quad \mathcal{S} := \mathcal{S}_f \cup \mathcal{S}_v.$$

When a tangential step is computed, the size of the step is restricted by a trust-region radius (see (2.29c) and (2.34c)). For convenience, we capture these radii by defining  $\delta_{-1}^t := 1$  and, for  $k \geq 0$ ,

$$\delta_k^t := \begin{cases} \delta_{k-1}^t & \text{if } k \notin \mathcal{T}, \\ \min\{\delta_k^v, \delta_k^f\} & \text{if } k \in \mathcal{T} \cap \mathcal{T}_{\mathcal{D}}, \\ \min\{\delta_k^v, \delta_k^f, \sqrt{\kappa_v v_k^{\max}}\} & \text{if } k \in \mathcal{T} \setminus \mathcal{T}_{\mathcal{D}}. \end{cases} \quad (2.57)$$

As a guide to salient properties of the various types of iterations we have defined, we provide the following lemma regarding basic facts that may be deduced from the design of our algorithm. Unless stated otherwise, reference to the tangential step  $t_k$  corresponds to the value used in Step 36 of Algorithm 1, i.e., the value after the possible reset in Step 29. For the purposes of this lemma, we assume that if the algorithm does not terminate during iteration  $k$ , then all steps of the algorithm during the iteration are well-defined. We prove this fact formally in the next subsection.

**Lemma 2.6.** *If Algorithm 1 does not terminate during the  $k$ th iteration, then the following hold.*

- (i) *If  $k \in \mathcal{N}$ , then  $\pi_k^v > 0$ ,  $m_k^v(0) - m_k^v(n_k^c) > 0$ ,  $m_k^v(0) - m_k^v(n_k) > 0$ , and  $n_k \neq 0$ .*
- (ii) *If  $n_k \neq 0$ , then  $k \in \mathcal{N}$ .*
- (iii) *If  $k \in \mathcal{T}$ , then  $\chi_k^f \geq \kappa_\chi \pi_k^f > 0$  and  $m_k^f(n_k) - m_k^f(n_k + t_k^c) > 0$ .*
- (iv) *If  $k \in \mathcal{T} \setminus \mathcal{T}_0$ , then  $t_k \neq 0$  and  $m_k^f(n_k) - m_k^f(n_k + t_k) > 0$ , while if  $k \in \mathcal{T}_0$ , then  $t_k = 0$  and (2.19) holds.*
- (v) *If  $t_k \neq 0$ , then  $k \in \mathcal{T} \setminus \mathcal{T}_0$ .*
- (vi)  *$k \in \mathcal{Y}$  if and only if  $n_k = t_k = 0$ .*
- (vii) *If  $k \in \mathcal{Y}$ , then  $k \in \mathcal{D}$  and  $\pi_k^f \leq \kappa_\omega \pi_{k-1}^f$  with  $\kappa_\omega \in (0, 1)$  defined as in (2.26).*

(viii) If  $k \notin \mathcal{D}$ , then  $k \in \mathcal{T} \setminus \mathcal{T}_{\mathcal{D}}$  and (2.34) holds.

(ix) If  $k \in \mathcal{D}$ , then the inequality in (2.47) holds.

(x)  $\mathcal{T}_{\mathcal{D}} \subseteq \mathcal{D}$ .

(xi) If  $k \in \mathcal{T} \setminus \mathcal{T}_{\mathcal{D}}$ , then  $n_k = 0$  and  $k \notin \mathcal{N}$ .

*Proof.* To prove part (i), let  $k \in \mathcal{N}$ , in which case we have that the conditions in Step 9 held true. This could occur only if  $\pi_k^v > 0$ , or if in (2.8) we had  $\pi_k^v > \omega_n(\pi_{k-1}^f) \geq 0$  or  $v_k \geq \kappa_{vv} v_k^{\max}$ . Thus, to prove that  $k \in \mathcal{N}$  implies  $\pi_k^v > 0$ , all that remains is to investigate the case when  $v_k \geq \kappa_{vv} v_k^{\max}$ . Since  $v_k^{\max} > 0$  by construction, this inequality implies that  $v_k > 0$ . If  $\pi_k^v = 0$ , then the algorithm would have terminated in Step 8 with an infeasible stationary point. Thus, we may again conclude that  $\pi_k^v > 0$ , which establishes this strict inequality for all  $k \in \mathcal{N}$ . Since  $\pi_k^v > 0$ , it follows from the definition of  $P_k$  and (2.7) that  $n = -P_k^2 J(x_k, s_k)^T c(x_k, s_k)$  is a direction of strict decrease for  $m_k^v(n)$ , from which it follows by (2.9) that  $m_k^v(0) - m_k^v(n_k^c) > 0$ . In turn, (2.12) implies the remainder of part (i).

Part (ii) follows since if  $n_k \neq 0$ , then the conditions in Step 9 must have held (or else the algorithm would have set  $n_k \leftarrow 0$ ), in which case  $k \in \mathcal{N}$ .

Next, we prove part (iii). If  $k \in \mathcal{T}$ , then it follows from Steps 16–25 of the algorithm that after the computation of  $y_k$  (and all dependent quantities) both (2.25a) and (2.25b) did not hold (implying that  $\pi_k^f > 0$ ), but (2.25c) did. Combining (2.25c) and the fact that  $\pi_k^f > 0$  shows that  $\nabla m_k^f(n_k)^T r_k \geq \kappa_\chi (\pi_k^f)^2 > 0$ , so that  $r_k$  is a direction of strict ascent for  $m_k^f$  at  $n_k$ . Combining this fact with (2.27)/(2.32) and (2.28)/(2.33) yields  $m_k^f(n_k) - m_k^f(n_k + t_k^c) > 0$ , as desired.

Building on the proof of part (iii), we next prove part (iv). If we have  $k \in \mathcal{T} \setminus \mathcal{T}_0$ , then we may combine  $m_k^f(n_k) - m_k^f(n_k + t_k^c) > 0$  with (2.29a)/(2.34a) to conclude that  $t_k \neq 0$  and  $m_k^f(n_k) - m_k^f(n_k + t_k) > 0$ , as desired. (Since  $k \notin \mathcal{T}_0$ , this tangential step was not reset to zero, so we have maintained  $t_k \neq 0$  in Step 36.) Finally, if  $k \in \mathcal{T}_0$ , it follows from Steps 15–29 that (2.19) holds, but that the algorithm reset  $t_k \leftarrow 0$ .

To prove part (v), we first note that if  $t_k \neq 0$ , then a tangential step was computed and thus  $k \in \mathcal{T}$ . Moreover, since  $t_k \neq 0$ , we know that  $k \notin \mathcal{T}_0$ , that means  $k \in \mathcal{T} \setminus \mathcal{T}_0$ , as desired.

We now prove part (vi). If  $n_k = t_k = 0$ , then  $d_k = 0$  and we have  $k \in \mathcal{Y}$  by the definition of  $\mathcal{Y}$ . Now, in order to derive a contradiction, suppose that  $k \in \mathcal{Y}$  (so that  $d_k = n_k + t_k = 0$ ), but suppose that  $n_k \neq 0$  and/or  $t_k \neq 0$ . Indeed, since  $n_k + t_k = 0$ , we must have  $n_k \neq 0$  and  $t_k \neq 0$ . It then follows from parts (ii) and (v) that  $k \in \mathcal{Y} \cap \mathcal{N} \cap (\mathcal{T} \setminus \mathcal{T}_0)$ . Consequently, from part (i) we have that  $m_k^v(0) > m_k^v(n_k)$ . This fact and the equation  $n_k + t_k = 0$  imply that (2.29d) can not be satisfied. However, according to Steps 22–23 of the algorithm, since  $k \in \mathcal{N}$  we compute  $t_k$  to satisfy (2.29), which is a contradiction.

To prove part (vii), suppose  $k \in \mathcal{Y}$ . It follows from part (vi) that  $n_k = t_k = 0$  so that (2.29d) holds (this means  $k \in \mathcal{D}$ ), and then from part (i) that  $k \notin \mathcal{N}$ . Hence, from Step 9 of the algorithm, it follows that (2.8) must be violated. Moreover, since  $n_k = 0$ , we also know that (2.19) holds and thus an oblique projected gradient  $r_k$  was computed (as stipulated in Step 16) to satisfy at least one of (2.25a), (2.25b) and (2.25c). In fact, under the conditions of this lemma, it follows that (2.25a) must not have held, so we know that either (2.25b) or (2.25c) is satisfied as a result of this calculation. Suppose that (2.25c) holds so that the algorithm would have proceeded to compute a tangential step and  $k \in \mathcal{T}$ . If  $k \notin \mathcal{T}_0$ , then it would follow from part (iv) that  $t_k \neq 0$ , which is a contradiction. Thus, we must have  $k \in \mathcal{T}_0$ , i.e., we reset  $t_k \leftarrow 0$  because the computed tangential step satisfied (2.30), but not (2.31). This is a contradiction because (2.31) would have been satisfied trivially since  $n_k = 0$ . Thus (2.25c) can not hold, which implies that (2.25b) must hold. Since we have shown that (2.25b) holds and that (2.8) does not hold, we conclude that  $\pi_k^f \leq \omega_t(\pi_k^v) \leq \omega_t(\omega_n(\pi_{k-1}^f)) \leq \kappa_\omega \pi_{k-1}^f$ , where we have used the monotonicity of  $\omega_t$  and (2.26).

To establish part (viii), let  $k \notin \mathcal{D}$ . It follows from part (vii) that  $k \notin \mathcal{Y}$ . Now, suppose that  $t_k = 0$ . Combining this with  $k \notin \mathcal{Y}$  implies from (vi) that  $n_k \neq 0$ , which may then be combined with (ii) to deduce that  $k \in \mathcal{N}$ . This fact along with (i) and the fact that  $t_k = 0$  implies that (2.29d) holds, and

hence  $k \in \mathcal{D}$ , which is a contradiction. Therefore, we must have  $t_k \neq 0$ , which from (v) implies that  $k \in \mathcal{T} \setminus \mathcal{T}_0$  and that the computed tangential step was not reset to zero. Thus,  $t_k$  satisfies either (2.29) or (2.34). Recalling that  $k \notin \mathcal{D}$  so that (2.29d) is not satisfied, we conclude that  $k \notin \mathcal{T}_\mathcal{D}$  and (2.34) must be satisfied.

To prove part (ix), suppose  $k \in \mathcal{D}$  so that (2.29d) holds. Then,

$$\begin{aligned} \Delta m_k^{v,d} &= m_k^v(0) - m_k^v(d_k) \\ &\geq m_k^v(0) - \kappa_{\text{tg}} m_k^v(0) - (1 - \kappa_{\text{tg}}) m_k^v(n_k) \\ &= (1 - \kappa_{\text{tg}}) (m_k^v(0) - m_k^v(n_k)) = (1 - \kappa_{\text{tg}}) \Delta m_k^{v,n}, \end{aligned} \quad (2.58)$$

which, since  $\kappa_{\text{cd}} \in (0, 1 - \kappa_{\text{tg}}]$ , means that the inequality in (2.47) holds, as desired.

To prove (x), let  $k \in \mathcal{T}_\mathcal{D}$ . It follows that a relaxed SQP tangential step  $t_k$  was computed to satisfy (2.29). Thus, if  $t_k$  is not reset to zero, we know that (2.29d) holds. However, if  $t_k$  was reset to zero, then (2.29d) holds trivially when  $n_k = 0$  and from parts (i) and (ii) when  $n_k \neq 0$ . We have shown in all cases that (2.29d) holds and therefore  $k \in \mathcal{D}$ .

Finally, to prove (xi), let  $k \in \mathcal{T} \setminus \mathcal{T}_\mathcal{D}$ . By lines 22–28 of Algorithm 1, it follows that (2.34) holds and  $k \notin \mathcal{N}$  for all  $k \in \mathcal{T} \setminus \mathcal{T}_\mathcal{D}$ . It then follows from part (ii) that  $n_k = 0$ .  $\square$

## 2.6 Well-posedness

The purpose of this section is to prove that Algorithm 1 is well-posed in the sense that if iteration  $k$  is reached, then in a reasonable implementation of the algorithm, all computations within iteration  $k$  will terminate finitely. Our first result shows important consequences of the slack reset procedure.

**Lemma 2.7.** *The slack reset (2.39) and (2.50) in Steps 40 and 42 yields  $s_k$  such that  $(x_k, s_k)$  satisfies  $s_k > 0$  and  $c(x_k, s_k) \geq 0$ .*

*Proof.* The fact that  $s_k > 0$  follows from the choice  $s_0 > 0$ , the fact that the slack reset (2.3) only possibly increases the slack variables (as shown in (2.4)), and the fact that the fraction-to-the-boundary rules in (2.11) and (2.29b)/(2.34b) hold when normal and tangential steps are computed.

We now prove that  $c(x_k, s_k) \geq 0$  holds. Prior to the slack reset performed in Steps 40 and 42, if  $[c(x_k, s_k)]_i \geq 0$ , then (2.3) leaves  $[s_k]_i$  unchanged so that  $[c(x_k, s_k)]_i \geq 0$  still holds. Otherwise, if  $[c(x_k, s_k)]_i < 0$ , then after the slack reset (2.3) we have that  $[c(x_k) + s_k]_i = 0$ , which completes the proof.  $\square$

Next, we prove that the Cauchy step for the normal step subproblem is well-defined.

**Lemma 2.8.** *If  $k \in \mathcal{N}$ , then the Cauchy step  $n_k^c$  defined by (2.9)–(2.10) is computed and satisfies*

$$m_k^v(0) - m_k^v(n_k^c) \geq \kappa_k^{\text{cn}} \pi_k^v \min\{\pi_k^v, \delta_k^v, 1 - \kappa_{\text{fbn}}\} > 0, \quad (2.59)$$

where

$$\kappa_k^{\text{cn}} := \frac{2}{\left(1 + \|J(x_k, s_k)P_k\|_2^2\right)} \in (0, 2].$$

*Proof.* Since  $k \in \mathcal{N}$ , we may observe from part (i) of Lemma 2.6 that  $\pi_k^v > 0$ . We now show that  $n_k^c(\alpha)$  (recall (2.9)) is feasible for (2.10) during any iteration  $k \in \mathcal{N}$  when

$$0 \leq \alpha \leq \frac{1}{\pi_k^v} \min\{\delta_k^v, \kappa_n \pi_k^v, (1 - \kappa_{\text{fbn}})\} =: \alpha_B. \quad (2.60)$$

Indeed, consider any  $\alpha \in [0, \alpha_B]$ . It then follows from the definitions of  $n_k^c(\alpha)$  and  $\pi_k^v$  that

$$\|P_k^{-1} n_k^c(\alpha)\|_2 = \|\alpha P_k J(x_k, s_k)^T c(x_k, s_k)\|_2 = \alpha \pi_k^v \leq \min\{\delta_k^v, \kappa_n \pi_k^v\}.$$

It also follows from the definitions of  $n_k^{Cs}(\alpha)$  and Lemma 2.7 that

$$\begin{aligned} [-n_k^{Cs}(\alpha)]_i &= \alpha [S_k]_{ii}^2 [c(x_k, s_k)]_i \leq \alpha [s_k]_i \|P_k J(x_k, s_k)^T c(x_k, s_k)\|_2 \\ &= \alpha \pi_k^v [s_k]_i \leq (1 - \kappa_{\text{fbn}}) [s_k]_i \quad \text{for } i = 1, 2, \dots, M, \end{aligned}$$

which implies that  $s_k + n_k^{Cs}(\alpha) \geq \kappa_{\text{fbn}} s_k$ . Overall,  $n_k^C(\alpha)$  is feasible for problem (2.5) for all  $\alpha \in [0, \alpha_B]$ .

Now, observe that the minimizer  $\alpha_N^C$  defined by (2.10) yields  $m_k^v(n_k^C) = m_k^v(n_k^C(\alpha_N^C)) \leq m_k^v(n_k^C(\alpha))$  for all  $\alpha \in [0, \alpha_B]$ . It then follows from [3, Lemma 1] with the quantities

$$“t” := \alpha_B, \quad “a” := 2 \|J(x_k, s_k) P_k^2 J(x_k, s_k)^T c(x_k, s_k)\|_2^2, \quad “b” := 2(\pi_k^v)^2 > 0,$$

the fact that

$$“a” \leq 2 \|J(x_k, s_k) P_k\|_2^2 \|P_k J(x_k, s_k)^T c(x_k, s_k)\|_2^2 = 2 \|J(x_k, s_k) P_k\|_2^2 (\pi_k^v)^2,$$

and the definition of  $\pi_k^v$  that

$$\begin{aligned} \frac{1}{2} m_k^v(0) - \frac{1}{2} m_k^v(n_k^C) &\geq \frac{“b”}{2} \min \left\{ \frac{“b”}{“a”}, “t” \right\} \\ &\geq \pi_k^v \min \left\{ \frac{(\pi_k^v)^2}{\|J(x_k, s_k) P_k\|_2^2 (\pi_k^v)^2}, \frac{\delta_k^v}{\pi_k^v}, \kappa_n, \frac{1 - \kappa_{\text{fbn}}}{\pi_k^v} \right\} \\ &= \pi_k^v \min \left\{ \frac{\pi_k^v}{1 + \|J(x_k, s_k) P_k\|_2^2}, \delta_k^v, \kappa_n \pi_k^v, 1 - \kappa_{\text{fbn}} \right\} > 0. \end{aligned}$$

This leads to the desired result since  $1 + \|J(x_k, s_k) P_k\|_2^2 \geq 1$  and  $\kappa_n \geq 1$ .  $\square$

Next we establish the remaining claims made in (2.2). (We remark that certain bounds established in the proof of this lemma are specified in more detail in Lemma 3.12.)

**Lemma 2.9.** *The slack reset (2.39) and (2.50) in Steps 40 and 42 yields  $s_k$  such that the pair  $(x_k, s_k)$  satisfies  $v_k \leq v_k^{\max}$  and, at the end of iteration  $k$ , we have  $v_{k+1}^{\max} \leq v_k^{\max}$ .*

*Proof.* Our proof is by induction. We have  $v_0 \leq v_0^{\max}$  by the initialization of  $v_0^{\max}$ . So now suppose that  $v_i \leq v_i^{\max}$  for  $i = 0, \dots, k-1$ , and in particular that  $v_{k-1} \leq v_{k-1}^{\max}$  at the start of the  $k-1$ st iteration. The slack reset in Steps 40 and 42 cannot increase the constraint violation (recall (2.4)), so that  $v_{k-1} \leq v_{k-1}^{\max}$  holds following slack reset. It is also clear from (2.35), (2.36) and (2.36) that for  $k-1 \in \mathcal{Y} \cup \mathcal{F}$  the inequality  $v_k \leq v_k^{\max}$  continues to hold at the start of iteration  $k$ . Hence, it remains to consider  $k-1 \in \mathcal{V}$ . If  $\rho_{k-1}^v < \eta_1$  or (2.47) does not hold (with  $k$  replaced by  $k-1$ ), then  $v_k \leq v_k^{\max}$  holds at the start of iteration  $k$  as a result of (2.53) and (2.55). Otherwise, it follows from Lemma 2.8, (2.12) and (2.47) that  $\Delta m_{k-1}^{v,d} > 0$  and thus  $v_k < v_{k-1}$  from  $\rho_{k-1}^v \geq \eta_1$ , (2.48) and (2.49). This implies that

$$v_k < v_k + \kappa_{t2} (v_{k-1} - v_k) < v_{k-1} \leq v_{k-1}^{\max} \tag{2.61}$$

as  $\kappa_{t2} \in (0, 1)$ , and hence from (2.52) that  $v_k^{\max} \leq v_{k-1}^{\max}$ . Combining (2.52) and (2.61), we have that  $v_k^{\max} \geq v_k + \kappa_{t2} (v_{k-1} - v_k) > v_k$ . Thus in all cases  $v_k \leq v_k^{\max}$ , and the induction is complete.

To establish that  $v_{k+1}^{\max} \leq v_k^{\max}$ , note that if  $k \notin \mathcal{V}$ , then  $v_{k+1}^{\max} \leftarrow v_k^{\max}$ , so all that remains is to consider  $k \in \mathcal{V}$ . Observing (2.52), we see again that  $v_{k+1}^{\max} \leftarrow v_k^{\max}$  if either (2.47) is violated or  $\rho_k^v < \eta_1$ . By contrast, if (2.47) holds and  $\rho_k^v \geq \eta_1$ , then we must have  $n_k \neq 0$  and from part (ii) of Lemma 2.6 that  $k \in \mathcal{N}$ . Moreover, it follows from (2.49), (2.48), (2.47), (2.12) and Lemma 2.8 as above that  $v_{k+1} < v_k$ , and then, since both terms in the max in (2.52) are smaller than  $v_k \leq v_k^{\max}$ , that  $0 < v_{k+1}^{\max} < v_k^{\max}$  as desired.  $\square$

Next, we show that the computation of the least-squares multipliers  $y_k$ —along with the accompanying quantities  $r_k$ ,  $\pi_k^f$ , and  $\chi_k^f$ —is well-defined. We prove this result under the following reasonable

assumption.

**Assumption 2.1.** *If (2.19) holds and the iterative solver employed to solve (2.21) is allowed to run for an infinite number of iterations, then it produces a bounded sequence  $\{y^{(i)}\}$  with  $y^{(0)} = 0$  such that*

$$\lim_{i \rightarrow \infty} \nabla m_k^{\mathcal{L}}(y^{(i)}) = 0. \quad (2.62)$$

**Lemma 2.10.** *If (2.19) holds and  $\{y^{(i)}\}$  is produced by an iterative solver employed to solve (2.21) that satisfies Assumption 2.1, then for some (finite) index  $i$  the vector  $y_k \leftarrow y^{(i)}$  yields  $r_k$ ,  $\pi_k^f$ , and  $\chi_k^f$  satisfying (2.25a), (2.25b), or (2.25c).*

*Proof.* For the purpose of deriving a contradiction, suppose that the iterative solver applied to solve (2.21) runs for an infinite number of iterations without satisfying (2.25a), (2.25b), or (2.25c). Under Assumption 2.1, the sequence  $\{y^{(i)}\}$  is bounded, so with (2.62) we have that it has a limit point  $y^\infty$  satisfying

$$0 = \nabla m_k^{\mathcal{L}}(y^\infty) = J(x_k, s_k) r_k(y^\infty). \quad (2.63)$$

Suppose that  $\pi_k^f(y^\infty) = 0$ . If  $v_k \leq \epsilon_v$ , then this implies that there exists some smallest index  $i$  such that with  $y_k \leftarrow y^{(i)}$  condition (2.25a) will be satisfied, which is a contradiction. Otherwise, if  $v_k > \epsilon_v$ , then we must have  $\pi_k^v > 0$  or else Algorithm 1 would have terminated in Step 8. It then follows from  $\pi_k^v > 0$  and  $\pi_k^f(y^\infty) = 0$  that there exists a smallest index  $i$  such that with  $y_k \leftarrow y^{(i)}$  condition (2.25b) will be satisfied, which is a contradiction. We have shown that  $\pi_k^f(y^\infty) > 0$ , which combined with (2.63) and

$$\nabla m_k^f(n_k) = P_k^{-2} r_k(y^\infty) - J(x_k, s_k)^T y^\infty$$

shows that

$$\chi_k^f(y^\infty) = \frac{r_k(y^\infty)^T \nabla m_k^f(n_k)}{\pi_k^f(y^\infty)} = \frac{r_k(y^\infty)^T (P_k^{-2} r_k(y^\infty) - J(x_k, s_k)^T y^\infty)}{\pi_k^f(y^\infty)} = \frac{(\pi_k^f(y^\infty))^2}{\pi_k^f(y^\infty)} = \pi_k^f(y^\infty). \quad (2.64)$$

If  $\nabla m_k^{\mathcal{L}}(0) = 0$ , then we have with (2.64) that  $y_k \leftarrow y^{(0)} = 0$  satisfies (2.25c), which is a contradiction. By contrast, if  $\nabla m_k^{\mathcal{L}}(0) \neq 0$ , then since  $\kappa_\chi \in (0, 1)$  we have from (2.64) and (2.62) that there is a smallest index  $i$  for which  $y_k \leftarrow y^{(i)}$  satisfies condition (2.25c), which is another contradiction.

We have arrived at a contradiction in all cases, so the iterative solver must terminate finitely.  $\square$

We now give a bound on the decrease in our barrier model provided by the Cauchy step  $t_k^{\mathcal{C}}$ .

**Lemma 2.11.** *If  $k \in \mathcal{T}$ , then the Cauchy step  $t_k^{\mathcal{C}}$  defined by (2.27)–(2.28) or (2.32)–(2.33) is computed and satisfies*

$$m_k^f(n_k) - m_k^f(n_k + t_k^{\mathcal{C}}) \geq \kappa_k^{\text{ct}} \pi_k^f \min \left\{ \pi_k^f, (1 - \kappa_{\text{B}}) \delta_k^t, (1 - \kappa_{\text{fbt}}) \kappa_{\text{fbn}} \right\} > 0,$$

where

$$\kappa_k^{\text{ct}} := \frac{\kappa_\chi^2}{2(1 + \|P_k G_k P_k\|_2)} \in (0, 1/2).$$

*Proof.* We first consider the case when  $k \in \mathcal{T}_{\mathcal{D}}$ , i.e., when the Cauchy step  $t_k^{\mathcal{C}}$  is computed from (2.27)–(2.28) with the trust region radius  $\delta_k^t = \min\{\delta_k^v, \delta_k^f\}$  (see (2.57)). It follows from part (iii) of Lemma 2.6 that  $\chi_k^f \geq \kappa_\chi \pi_k^f > 0$  so that  $\nabla m_k^f(n_k)^T r_k \geq \kappa_\chi (\pi_k^f)^2 > 0$ . We now show that  $t_k^{\mathcal{C}}(\alpha)$  (recall (2.27)) is feasible for (2.28) during iteration  $k \in \mathcal{T}_{\mathcal{D}}$  when

$$0 \leq \alpha \leq \frac{1}{\pi_k^f} \min \left\{ (1 - \kappa_{\text{B}}) \delta_k^t, (1 - \kappa_{\text{fbt}}) \kappa_{\text{fbn}} \right\} =: \alpha_{\text{B}}.$$

Indeed, consider any  $\alpha \in [0, \alpha_B]$ . It follows from the definitions of  $t_k^C(\alpha)$ ,  $r_k$ , and  $\alpha_B$  that

$$\|P_k^{-1}t_k^C(\alpha)\|_2 = \|P_k^{-1}\alpha r_k\|_2 = \alpha\|P_k^{-1}r_k\|_2 = \alpha\pi_k^f \leq (1 - \kappa_B)\delta_k^t. \quad (2.65)$$

Using the triangle inequality, (2.19) (which must hold since  $k \in \mathcal{T}_D \subseteq \mathcal{T}$ ), (2.57), and (2.65), we then have

$$\|P_k^{-1}(n_k + t_k^C(\alpha))\|_2 \leq \|P_k^{-1}n_k\|_2 + \|P_k^{-1}t_k^C(\alpha)\|_2 \leq \kappa_B\delta_k^t + (1 - \kappa_B)\delta_k^t \leq \delta_k^t = \min\{\delta_k^v, \delta_k^f\}, \quad (2.66)$$

which shows that  $t_k^C(\alpha)$  satisfies the first constraint in problem (2.28). To show that  $t_k^{Cs}(\alpha)$  also satisfies the second constraint in problem (2.28), first observe that if  $[t_k^{Cs}(\alpha)]_i = [-\alpha r_k^s]_i \geq 0$ , then  $[s_k + n_k^s + t_k^{Cs}(\alpha)]_i \geq [s_k + n_k^s]_i \geq \kappa_{\text{fbt}}[s_k + n_k^s]_i \geq 0$  since  $\kappa_{\text{fbt}} \in (0, 1)$ . Thus it suffices to consider  $i$  such that  $[r_k^s]_i > 0$ . It follows from the definitions of  $\alpha_B$  and  $\pi_k^f$ , (2.22), the fact that  $[r_k^s]_i > 0$ , Lemma 2.7, and (2.11) that

$$\begin{aligned} \alpha \leq \alpha_B &\leq \frac{(1 - \kappa_{\text{fbt}})\kappa_{\text{fbn}}}{\pi_k^f} \leq \frac{(1 - \kappa_{\text{fbt}})\kappa_{\text{fbn}}}{\|S_k^{-1}r_k^s\|_2} \\ &\leq \frac{(1 - \kappa_{\text{fbt}})\kappa_{\text{fbn}}}{|[r_k^s]_i/[S_k]_{ii}|} = \frac{(1 - \kappa_{\text{fbt}})\kappa_{\text{fbn}}[s_k]_i}{[r_k^s]_i} \leq \frac{(1 - \kappa_{\text{fbt}})[s_k + n_k^s]_i}{[r_k^s]_i}. \end{aligned}$$

Using the definition of  $t_k^{Cs}(\alpha)$  and the previous inequality leads to

$$[-t_k^{Cs}(\alpha)]_i = \alpha[r_k^s]_i \leq (1 - \kappa_{\text{fbt}})[s_k + n_k^s]_i$$

from which we may conclude overall that  $[s_k + n_k^s + t_k^{Cs}(\alpha)]_i \geq \kappa_{\text{fbt}}[s_k + n_k^s]_i$  for  $i = 1, 2, \dots, M$ . This proves that  $t_k^{Cs}(\alpha)$  satisfies the second constraint in problem (2.28), and completes the proof that  $t_k^C(\alpha)$  is feasible for problem (2.28) for all  $\alpha \in [0, \alpha_B]$ .

We now observe that the minimizer  $\alpha_T^C$  of (2.28) yields  $m_k^f(n_k + t_k^C) \equiv m_k^f(n_k + t_k^C(\alpha_T^C)) \leq m_k^f(n_k + t_k^C(\alpha))$  for all  $\alpha \in [0, \alpha_B]$ . We also have from the Cauchy-Schwarz and standard norm inequalities that

$$|r_k^T G_k r_k| = \left| (\nabla m_k^f(n_k) + J(x_k, s_k)^T y_k)^T P_k^2 G_k P_k^2 (\nabla m_k^f(n_k) + J(x_k, s_k)^T y_k)^T \right| \leq (\pi_k^f)^2 \|P_k G_k P_k\|_2.$$

It then follows from [3, Lemma 1] with the quantities

$$“t” := \alpha_B, \quad “a” := |r_k^T G_k r_k|, \quad “b” := \nabla m_k^f(n_k)^T r_k > 0,$$

(the strict inequality was shown in the first line of this proof) that

$$\begin{aligned} m_k^f(n_k) - m_k^f(n_k + t_k^C) &\geq \frac{“b”}{2} \min \left\{ \frac{“b”}{“a”}, “t” \right\} \\ &\geq \frac{\nabla m_k^f(n_k)^T r_k}{2} \min \left\{ \frac{\nabla m_k^f(n_k)^T r_k}{(\pi_k^f)^2 \|P_k G_k P_k\|_2}, \frac{(1 - \kappa_B)\delta_k^t}{\pi_k^f}, \frac{(1 - \kappa_{\text{fbt}})\kappa_{\text{fbn}}}{\pi_k^f} \right\} \\ &= \frac{\nabla m_k^f(n_k)^T r_k}{2\pi_k^f} \min \left\{ \frac{\nabla m_k^f(n_k)^T r_k}{\pi_k^f (1 + \|P_k G_k P_k\|_2)}, (1 - \kappa_B)\delta_k^t, (1 - \kappa_{\text{fbt}})\kappa_{\text{fbn}} \right\} \\ &= \frac{\chi_k^f}{2} \min \left\{ \frac{\chi_k^f}{(1 + \|P_k G_k P_k\|_2)}, (1 - \kappa_B)\delta_k^t, (1 - \kappa_{\text{fbt}})\kappa_{\text{fbn}} \right\} \\ &\geq \frac{\kappa_\chi^2 \pi_k^f}{2(1 + \|P_k G_k P_k\|_2)} \min \left\{ \pi_k^f, (1 - \kappa_B)\delta_k^t, (1 - \kappa_{\text{fbt}})\kappa_{\text{fbn}} \right\}, \end{aligned}$$

where we have used  $1 + \|P_k G_k P_k\|_2 \geq 1$  and  $\chi_k^f \geq \kappa_\chi \pi_k^f$  with  $\kappa_\chi \in (0, 1)$  for the last inequality.

The proof for the case  $k \in \mathcal{T} \setminus \mathcal{T}_D$  is similar, but uses  $\delta_k^t = \min\{\delta_k^v, \delta_k^f, \sqrt{\kappa_v v_k^{\max}}\}$ , (2.32) instead of (2.27), (2.33) instead of (2.28), and  $n_k = 0$  (see part (xi) of Lemma 2.6) for  $k \in \mathcal{T} \setminus \mathcal{T}_D$ .  $\square$

Finally, we turn our attention to the tangential step computation. The following result shows one way to find a tangential step  $t_k$  that satisfies the required conditions described in Section 2.3.

**Lemma 2.12.** *If (2.19) holds and  $\{y^{(i)}\}$  is produced by an iterative solver employed to solve (2.21) that satisfies Assumption 2.1, then for some (finite) index  $i$  the vector  $y_k \leftarrow y^{(i)}$  yields  $r_k$  such that either*

(i) *the Cauchy point  $t_k^c$  defined by (2.27)–(2.28) satisfies (2.29), or*

(ii) *the Cauchy point  $t_k^c$  defined by (2.32)–(2.33) satisfies (2.34).*

*Proof.* As in the proof of Lemma 2.10, in order to derive contradictions, suppose that the iterative solver employed to solve (2.21) runs for an infinite number of iterations without yielding the desired result, in which case we have under Assumption 2.1 that the sequence  $\{y^{(i)}\}$  has a limit point  $y^\infty$  satisfying (2.63). That is, as  $i \rightarrow \infty$ , we have  $r_k(y^{(i)}) \rightarrow r_k(y^\infty) \in \text{Null}(J(x_k, s_k))$ . We introduce the notation  $t_k^c(i) := t_k^c$  when  $t_k^c$  is the Cauchy point defined by (2.27)–(2.28) with  $r_k = r_k(y^{(i)})$  associated with the relaxed tangential subproblem, and  $t_k^{cv}(i) := t_k^{cv}$  when  $t_k^c$  is the Cauchy point defined by (2.32)–(2.33) with  $r_k = r_k(y^{(i)})$  associated with the very-relaxed tangential subproblem. We observe from (2.27) and (2.32), the constraints of (2.28) and (2.33), and the fact that  $r_k(y^\infty) \in \text{Null}(J(x_k, s_k))$  that there exist vectors  $t_k^{cr}(\infty)$  and  $t_k^{cv}(\infty)$  such that  $t_k^{cr}(i) \rightarrow t_k^{cr}(\infty) \in \text{Null}(J(x_k, s_k))$  and  $t_k^{cv}(i) \rightarrow t_k^{cv}(\infty) \in \text{Null}(J(x_k, s_k))$ .

By definition, the Cauchy point  $t_k^{cr}(i)$  satisfies (2.29a)–(2.29c) for all  $i$ . Similarly, the Cauchy point  $t_k^{cv}(i)$  satisfies (2.34a)–(2.34c) for all  $i$ . Thus, to reach contradictions, we need only show that for sufficiently large  $i$  either  $t_k^{cr}(i)$  satisfies (2.29d) or  $t_k^{cv}$  satisfies (2.34d).

Suppose that  $n_k \neq 0$ , in which case part (ii) of Lemma 2.6 implies that  $k \in \mathcal{N}$ . It then follows from part (i) of Lemma 2.6 that  $m_k^v(n_k) < v_k$ , and thus the right-hand side of (2.29d) is strictly greater than  $m_k^v(n_k)$ . Therefore, since  $t_k^{cr}(\infty) \in \text{Null}(J(x_k, s_k))$ , there exists some smallest index  $i$  such that  $t_k^{cr}(i)$  satisfies (2.29d), which is to say that statement (i) holds, which is a contradiction.

Now suppose that  $n_k = 0$ , in which case part (i) of Lemma 2.6 implies that  $k \notin \mathcal{N}$ . By virtue of (2.8), this must mean that  $v_k < \kappa_{vv} v_k^{\max}$ . It follows from the facts that  $n_k = 0$ ,  $v_k < \kappa_{vv} v_k^{\max}$ ,  $\kappa_{tt} \in (\kappa_{vv}, 1)$ , and  $t_k^{cv}(i) \rightarrow t_k^{cv}(\infty) \in \text{Null}(J(x_k, s_k))$  that  $t_k^{cv}(i)$  satisfies (2.34d) for all sufficiently large  $i$ . We have reached the contradiction that statement (ii) holds.  $\square$

### 3 Convergence of the Trust-Funnel Algorithm for Solving the Barrier Subproblem

Our analysis requires the following assumption that is assumed to hold for the remainder of the paper.

**Assumption 3.1.** *The sequence of iterates  $\{x_k\}$  is contained in a compact set.*

The following is an immediate consequence of Assumptions 1.1 and 3.1.

**Lemma 3.1.** *There exists a constant  $\kappa_H \geq 1$  such that, for all  $k$  and  $i = 1, 2, \dots, M$ , we have*

$$\max\{1, \|g(x_k)\|_2, \|c(x_k)\|_2, \|J(x_k)\|_2, \|\nabla_{xx}f(x_k)\|_2, \|\nabla_{xx}c_i(x_k)\|_2\} \leq \kappa_H.$$

We may now prove that important sequences related to our method are uniformly bounded.

**Lemma 3.2.** *There exists a constant  $\kappa_{ub} \geq \kappa_H \geq 1$  such that, for all  $k$ , we have*

$$\max\{v_k, \|s_k\|_2, \|J(x_k, s_k)^T c(x_k, s_k)\|_2, \pi_k^v, \|P_k J(x_k, s_k)^T\|_2, \|P_k G_k P_k\|_2, \|P_k \nabla f(x_k, s_k)\|_2\} \leq \kappa_{ub}.$$

*Proof.* The result is clearly true if the algorithm terminates finitely. Otherwise, it follows from Lemma 2.9 that  $v_k \leq v_k^{\max} \leq v_0^{\max}$  for all  $k$ , which proves that  $\{v_k\}$  can be bounded as claimed. Combining this with the reverse triangle inequality yields

$$\|s_k\|_2 - \|c(x_k)\|_2 \leq \|c(x_k) + s_k\|_2 = \|c(x_k, s_k)\|_2 \leq \sqrt{v_0^{\max}} \text{ for all } k.$$

We may deduce from this bound and Lemma 3.1 that  $\{\|s_k\|_2\}$  can be bounded as claimed. It then follows from the triangle inequality that

$$\|J(x_k, s_k)^T c(x_k, s_k)\|_2 \leq \left\| \begin{pmatrix} J(x_k)^T c(x_k, s_k) \\ 0 \end{pmatrix} \right\|_2 + \left\| \begin{pmatrix} 0 \\ c(x_k, s_k) \end{pmatrix} \right\|_2,$$

which may then be combined with the Cauchy Schwarz inequality, Lemma 3.1, and the boundedness of  $\{v_k\}$  to conclude that  $\{\|J(x_k, s_k)^T c(x_k, s_k)\|_2\}$  can be bounded as claimed. The boundedness of  $\{\pi_k^v\}$  follows from that of  $\{\|s_k\|_2\}$  and  $\{\|J(x_k, s_k)^T c(x_k, s_k)\|_2\}$ . It then follows from the boundedness of  $\{\|s_k\|_2\}$  and Lemma 3.1 that  $\{\|P_k J(x_k, s_k)^T\|_2\}$  can be bounded as claimed. The boundedness of  $\|P_k G_k P_k\|_2$  follows from the definition of  $P_k$ , the boundedness of  $\{\|s_k\|_2\}$ , (2.16), (2.17), Assumptions 1.1 and 3.1, and (2.18). Finally, it follows from Lemma 3.1 and the fact that  $P_k \nabla f(x_k, s_k) = (g(x_k), -\mu e)$  that  $\{\|P_k \nabla f(x_k, s_k)\|_2\}$  can be bounded as claimed.  $\square$

Using Lemma 3.2, we may now improve the Cauchy decrease bounds provided in Lemmas 2.8 and 2.11 by making the leading constants independent of the iteration number  $k$ .

**Lemma 3.3.** *For all  $k$ , the following hold:*

- (i) *If  $k \in \mathcal{N}$ , then the Cauchy step  $n_k^c$  defined by (2.9)–(2.10) is computed and satisfies*

$$m_k^v(0) - m_k^v(n_k^c) \geq \kappa_{\text{cn}} \pi_k^v \min\{\pi_k^v, \delta_k^v, 1 - \kappa_{\text{fbn}}\} > 0$$

*for some constant  $\kappa_{\text{cn}} \in (0, 2]$  independent of  $k$ .*

- (ii) *If  $k \in \mathcal{T}$ , then the Cauchy step  $t_k^c$  defined by (2.27)–(2.28) or (2.32)–(2.33) is computed and satisfies*

$$m_k^f(n_k) - m_k^f(n_k + t_k^c) \geq \kappa_{\text{ct}} \pi_k^f \min\left\{\pi_k^f, (1 - \kappa_{\text{B}}) \delta_k^f, (1 - \kappa_{\text{fbt}}) \kappa_{\text{fbn}}\right\} > 0$$

*for some constant  $\kappa_{\text{ct}} \in (0, 1/2]$  independent of  $k$ .*

*Proof.* The results follow from Lemmas 2.8 and 2.11 along with Lemma 3.2.  $\square$

We require the next lemma that bounds the size of the trial step in different scenarios.

**Lemma 3.4.** *If Algorithm 1 does not terminate during iteration  $k$ , then the following holds:*

$$\|P_k^{-1} d_k\|_2 \begin{cases} = \|P_k^{-1} n_k\|_2 \leq \min\{\delta_k^v, \kappa_n \pi_k^v\} & \text{if } k \notin \mathcal{T}, \\ = \|P_k^{-1} n_k\|_2 \leq \min\{\delta_k^v, \delta_k^f, \kappa_n \pi_k^v\} & \text{if } k \in \mathcal{T}_0, \\ \leq \delta_k^t & \text{if } k \in \mathcal{T} \setminus \mathcal{T}_0. \end{cases}$$

*In particular, for all  $k$ , we have  $\|P_k^{-1} d_k\|_2 \leq \delta_k^v$ .*

*Proof.* Let  $k \notin \mathcal{T}$ , from which we have under the conditions of the lemma that  $t_k \leftarrow 0$  and  $d_k = n_k$ . If  $n_k = 0$ , then the result holds trivially. Conversely, if  $n_k \neq 0$ , then part (ii) of Lemma 2.6 implies that  $k \in \mathcal{N}$  and the result follows from (2.11).

Next, let  $k \in \mathcal{T}$ . First, if  $k \in \mathcal{T}_0$ , then it follows from part (iv) of Lemma 2.6 that  $t_k = 0$  and (2.19) holds. Combining this with  $d_k = n_k + t_k = n_k$ , (2.11), and the fact that  $\kappa_{\text{B}} \in (0, 1)$  shows that

$$\|P_k^{-1} d_k\|_2 = \|P_k^{-1} n_k\|_2 \leq \min\{\kappa_{\text{B}} \min\{\delta_k^v, \delta_k^f\}, \delta_k^v, \kappa_n \pi_k^v\} \leq \min\{\delta_k^v, \delta_k^f, \kappa_n \pi_k^v\},$$

as desired. Second, if  $k \in \mathcal{T}_{\mathcal{D}} \setminus \mathcal{T}_0$ , then the result follows from (2.29c) and the definition (2.57). Third, if  $k \in \mathcal{T} \setminus \mathcal{T}_{\mathcal{D}}$ , then the result follows from (2.34c) and the definition (2.57).  $\square$

We now bound the discrepancies between the problem functions and their corresponding models.

**Lemma 3.5.** *The following hold:*

(i) *There exists a constant  $\kappa_{\mathcal{G}} > 0$  independent of  $k$  such that*

$$|f(x_k + d_k^x, s_k + d_k^s) - m_k^f(d_k)| \leq \kappa_{\mathcal{G}} \|P_k^{-1} d_k\|_2^2 \quad \text{for all } k. \quad (3.1)$$

(ii) *There exist constants  $\kappa_{\mathcal{C}} \geq 2\kappa_{\mathcal{H}} \geq 2$  and  $\{\kappa_{v1}, \kappa_{v2}\} \geq 2$  independent of  $k$  such that*

$$|v(x_k + d_k^x, s_k + d_k^s) - m_k^v(d_k)| \leq \kappa_{\mathcal{C}} \|P_k^{-1} d_k\|_2^2 \quad \text{for all } k \quad (3.2)$$

and

$$|v(x_k + d_k^x, s_k + d_k^s) - m_k^v(d_k)| \leq \kappa_{v1} \|P_k^{-1} d_k\|_2^3 + \kappa_{v2} \|c(x_k, s_k)\|_2 \|P_k^{-1} d_k\|_2^2 \quad \text{for all } k. \quad (3.3)$$

*Proof.* We first prove part (i). By the triangle inequality, we have

$$\begin{aligned} & |f(x_k + d_k^x, s_k + d_k^s) - m_k^f(d_k)| \\ & \leq |f(x_k + d_k^x) - f(x_k) - \nabla f(x_k)^T d_k^x - \frac{1}{2} d_k^{xT} \nabla_{xx} \mathcal{L}(x_k, y_k^{\mathcal{B}}) d_k^x| \\ & + \left| -\mu \sum_{i=1}^M \ln([s_k + d_k^s]_i) + \mu \sum_{i=1}^M \ln([s_k]_i) + \mu e^T S_k^{-1} d_k^s - \frac{1}{2} d_k^{sT} D_k d_k^s \right|. \end{aligned} \quad (3.4)$$

Under Assumptions 1.1 and 3.1, and by (2.17), there exists a constant  $\kappa_{\mathcal{G}1} > 0$  such that

$$|f(x_k + d_k^x) - f(x_k) - \nabla f(x_k)^T d_k^x - \frac{1}{2} d_k^{xT} \nabla_{xx} \mathcal{L}(x_k, y_k^{\mathcal{B}}) d_k^x| \leq \kappa_{\mathcal{G}1} \|d_k^x\|_2^2. \quad (3.5)$$

Moreover, note that for each  $i \in \{1, \dots, M\}$ , we have by (2.11) and (2.29b)/(2.34b) that  $[s_k]_i + [d_k^s]_i \geq \kappa_{\text{fbt}} \kappa_{\text{fbn}} [s_k]_i > 0$  for all  $k$  regardless of whether a tangential step  $t_k$  was computed. The mean-value theorem yields  $\ln([s_k]_i + [d_k^s]_i) - \ln[s_k]_i = [d_k^s]_i / \xi_i$ , where  $\xi_i$  lies between  $[s_k]_i$  and  $[s_k]_i + [d_k^s]_i$ . Hence

$$\begin{aligned} \left| \ln([s_k]_i + [d_k^s]_i) - \ln[s_k]_i - \frac{[d_k^s]_i}{[s_k]_i} \right| & \leq \sup_{\xi \in [[s_k]_i, [s_k]_i + [d_k^s]_i]} \left| \frac{[d_k^s]_i}{\xi} - \frac{[d_k^s]_i}{[s_k]_i} \right| \\ & = \frac{[s_k]_i}{[s_k]_i + [d_k^s]_i} \left( \frac{[d_k^s]_i}{[s_k]_i} \right)^2 \leq \frac{1}{\kappa_{\text{fbt}} \kappa_{\text{fbn}}} \left( \frac{[d_k^s]_i}{[s_k]_i} \right)^2, \end{aligned}$$

where in the middle equation we have used the fact that the sup occurs at  $\xi = [s_k]_i + [d_k^s]_i$ . Hence, by (2.18) and Lemma 3.2, we have that

$$\begin{aligned} & \left| -\mu \sum_{i=1}^M \ln([s_k + d_k^s]_i) + \mu \sum_{i=1}^M \ln([s_k]_i) + \mu e^T S_k^{-1} d_k^s - \frac{1}{2} d_k^{sT} D_k d_k^s \right| \\ & \leq \frac{1}{\kappa_{\text{fbt}} \kappa_{\text{fbn}}} d_k^{sT} (\mu S_k^{-2}) d_k^s + \frac{1}{2} |d_k^{sT} D_k d_k^s| \leq \kappa_{\mathcal{G}2} \|S_k^{-1} d_k^s\|_2^2. \end{aligned} \quad (3.6)$$

where  $\kappa_{\mathcal{G}2} = \mu / \kappa_{\text{fbt}} \kappa_{\text{fbn}} + \frac{1}{2} \kappa_{\text{ub}}^2 \kappa_{\mathcal{D}} > 0$ . The result now follows from (3.4)–(3.6), and Lemma 3.4 with  $\kappa_{\mathcal{G}} := \kappa_{\mathcal{G}1} + \kappa_{\mathcal{G}2}$ .

Part (ii) follows as for [25, Lemma 3.6] and uses Assumptions 1.1 and 3.1 and Lemmas 3.2 and 3.4.  $\square$

We now prove an important fact about  $v$ -iterations, namely, that if  $k \in \mathcal{V}$  and the trust region radii or  $v_k^{\max}$  is sufficiently small, then  $k \in \mathcal{D}$ , that is  $t_k$  is a relaxed SQP tangential step.

**Lemma 3.6.** *If  $k \in \mathcal{V}$  and*

$$\min\{\delta_k^v, \delta_k^f, \sqrt{\kappa_v v_k^{\max}}\} \leq \frac{(1 - \kappa_{tt})}{\kappa_v \kappa_{v1} + \kappa_{v2} \sqrt{\kappa_v}} =: \kappa_{\mathcal{V}}, \quad (3.7)$$

then  $k \in \mathcal{D}$ .

*Proof.* For a proof by contradiction, suppose that (3.7) holds while  $k \in \mathcal{V} \setminus \mathcal{D}$ . We show that all of the conditions of an  $f$ -iteration are satisfied, implying that  $k \in \mathcal{F}$ , contradicting the supposition that  $k \in \mathcal{V}$ .

Since  $k \notin \mathcal{D}$ , we have from part (viii) of Lemma 2.6 that  $k \in \mathcal{T} \setminus \mathcal{T}_{\mathcal{D}}$  and (2.34) holds. Then, since  $\mathcal{T}_0 \subseteq \mathcal{T}_{\mathcal{D}}$ , it follows that  $k \in \mathcal{T} \setminus \mathcal{T}_0$ , so by part (iv) of Lemma 2.6 we have  $t_k \neq 0$ . Moreover,  $k \in \mathcal{T} \setminus \mathcal{T}_0$  implies by Lemma 3.4 that  $\|P_k^{-1} d_k\|_2 \leq \delta_k^t$ , which along with the fact that  $k \in \mathcal{T} \setminus \mathcal{T}_{\mathcal{D}}$  and (2.57) implies

$$\|P_k^{-1} d_k\|_2 \leq \min\{\delta_k^v, \delta_k^f, \sqrt{\kappa_v v_k^{\max}}\} \leq \sqrt{\kappa_v v_k^{\max}} \quad \text{and} \quad \|P_k^{-1} d_k\|_2^2 \leq (\min\{\delta_k^v, \delta_k^f, \sqrt{\kappa_v v_k^{\max}}\})^2 \leq \kappa_v v_k^{\max}. \quad (3.8)$$

Combining these facts with (3.3), the reverse triangle inequality, (2.34c)–(2.34d), Lemma 2.9, and (3.7), we have

$$\begin{aligned} v(x_k + d_k^x, s_k + d_k^s) &\leq \kappa_{tt} v_k^{\max} + \kappa_{v1} \|P_k^{-1} d_k\|_2^3 + \kappa_{v2} \sqrt{v_k^{\max}} \|P_k^{-1} d_k\|_2^2 \\ &\leq \kappa_{tt} v_k^{\max} + \kappa_{v1} \kappa_v v_k^{\max} \min\{\delta_k^v, \delta_k^f, \sqrt{\kappa_v v_k^{\max}}\} + \kappa_{v2} \sqrt{\kappa_v} v_k^{\max} \min\{\delta_k^v, \delta_k^f, \sqrt{\kappa_v v_k^{\max}}\} \leq v_k^{\max} \end{aligned}$$

so (2.36) holds. Next, we know from part (xi) of Lemma 2.6 that  $n_k = 0$ . Combining this fact with part (iv) of Lemma 2.6 shows that (2.31) holds. Thus, all of the conditions of an  $f$ -iteration are satisfied, so the result follows as described.  $\square$

Lemmas 3.4 and 3.6 have the following useful consequence.

**Lemma 3.7.** *There exists a constant  $\kappa_{n\Delta 2} > 0$  such that if  $k \in \mathcal{V}$  and*

$$\min\{\delta_k^v, \delta_k^f\} \leq \min\{1, \kappa_{\mathcal{V}}, \kappa_{n\Delta 2} \pi_k^v\}, \quad (3.9)$$

where  $\kappa_{\mathcal{V}}$  is defined in (3.7), then  $k \in \mathcal{N}$ .

*Proof.* We first note that Lemmas 3.1, 3.2, and 2.9 imply that there exists a constant  $\kappa_{\pi} > 0$  independent of  $k$  such that

$$(\pi_k^v)^2 \leq \kappa_{\pi} v_k \leq \kappa_{\pi} v_k^{\max}. \quad (3.10)$$

Let  $k \in \mathcal{V}$  and (3.9) hold. Then, it follows from Lemma 3.6 that  $k \in \mathcal{D}$ , so  $k \in \mathcal{V} \cap \mathcal{D}$ . Now, in order to derive a contradiction, suppose that  $k \in (\mathcal{V} \cap \mathcal{D}) \setminus \mathcal{N}$ . Since  $k \notin \mathcal{N}$ , we have from part (ii) of Lemma 2.6 that  $n_k = 0$ . Then, since  $k \in \mathcal{V}$ , we must have  $t_k \neq 0$  (since otherwise part (vi) of Lemma 2.6 would imply that  $k \in \mathcal{Y}$ , which is a contradiction). Moreover,  $t_k \neq 0$  and  $k \in \mathcal{D}$  imply that (2.29d) holds. At the same time,  $k \notin \mathcal{N}$  implies that (2.8) does not hold, so  $v_k < \kappa_{vv} v_k^{\max}$ . This bound, (3.3), (2.29d),  $n_k = 0$ , (2.57), and Lemmas 2.9, 3.1, 3.2, and 3.4 then show that for  $\kappa_{v3} := \sqrt{v_0^{\max} \kappa_{v2}} > 0$  we have

$$v(x_k + d_k^x, s_k + d_k^s) < \kappa_{vv} v_k^{\max} + \kappa_{v1} (\min\{\delta_k^v, \delta_k^f\})^3 + \kappa_{v3} (\min\{\delta_k^v, \delta_k^f\})^2,$$

which, when combined with (3.9), (3.10), and

$$\kappa_{n\Delta 2} := \sqrt{\frac{(1 - \kappa_{vv})}{\kappa_{\pi} (\kappa_{v1} + \kappa_{v3})}} > 0,$$

yields

$$\begin{aligned} v(x_k + d_k^x, s_k + d_k^s) &< \kappa_{vv} v_k^{\max} + (\kappa_{v1} + \kappa_{v3})(\min\{\delta_k^v, \delta_k^f\})^2 \leq \kappa_{vv} v_k^{\max} + (\kappa_{v1} + \kappa_{v3}) \kappa_{n\Delta 2}^2 (\pi_k^v)^2 \\ &= \kappa_{vv} v_k^{\max} + \frac{(1 - \kappa_{vv})}{\kappa_\pi} (\pi_k^v)^2 \leq \kappa_{vv} v_k^{\max} + (1 - \kappa_{vv}) v_k^{\max} = v_k^{\max} \end{aligned}$$

so that (2.36) holds. Combining this with  $t_k \neq 0$  and the observation that (2.31) holds since  $\Delta m_k^{f,d} = \Delta m_k^{f,t}$  (recall  $n_k = 0$ ) shows that  $k \in \mathcal{F}$ , which is a contradiction. Thus, we must conclude that  $k \in \mathcal{N}$ .  $\square$

We now prove a relationship between the trust-region radii and a guarantee of a successful iteration.

**Lemma 3.8.** *The following hold:*

(i) *If  $k \in \mathcal{F}$  and*

$$\delta_k^t \leq \min \left\{ \frac{(1 - \kappa_{\text{fbt}}) \kappa_{\text{fbn}}}{1 - \kappa_{\text{B}}}, \frac{\pi_k^f}{1 - \kappa_{\text{B}}}, \frac{\kappa_\delta \kappa_{\text{ct}} (1 - \kappa_{\text{B}}) (1 - \eta_2) \pi_k^f}{\kappa_{\text{G}}} \right\} =: \min\{\kappa_{\Delta f1}, \kappa_{\Delta f2} \pi_k^f\} \quad (3.11)$$

*then  $\rho_k^f \geq \eta_2$ ,  $k \in \mathcal{S}_f$ , and  $\delta_{k+1}^f \geq \delta_k^f$ .*

(ii) *If  $k \in \mathcal{V}$  and*

$$\delta_k^v \leq \min \left\{ \kappa_{\mathcal{V}}, \pi_k^v, 1 - \kappa_{\text{fbn}}, \frac{\kappa_{\text{cd}} \kappa_{\text{cn}} \pi_k^v (1 - \eta_2)}{\kappa_{\text{C}}}, \kappa_{n\Delta 2} \pi_k^v \right\} =: \min\{\kappa_{\Delta c1}, \kappa_{\Delta c2} \pi_k^v\}, \quad (3.12)$$

*then  $k \in \mathcal{N} \cap \mathcal{D} \cap \mathcal{S}_v$ ,  $\rho_k^v \geq \eta_2$ , and  $\delta_{k+1}^v \geq \delta_k^v$ .*

*Proof.* For part (i), the proof that  $\rho_k^f \geq \eta_2$ , which implies that  $k \in \mathcal{S}_f$ , is the same as for [5, Theorem 6.4.2] and uses (2.37), (2.31) (which holds since  $k \in \mathcal{F}$ ), (2.29a)/(2.34a), part (ii) of Lemma 3.3, (3.11), (3.1), the fact that  $t_k \neq 0$ , and Lemma 3.4. The fact that  $\delta_{k+1}^f \geq \delta_k^f$  then follows from (2.40) and (2.43).

To prove part (ii), we first observe from (3.12) that  $\pi_k^v > 0$  since  $\delta_k^v > 0$  by construction in the algorithm. Furthermore, (3.12) and Lemma 3.7 imply that  $k \in \mathcal{N}$ , while (3.12) and Lemma 3.6 ensure that  $k \in \mathcal{D}$ . We now conclude from part (ix) of Lemma 2.6 that the inequality in (2.47) holds. The fact that  $k \in \mathcal{S}_v$  and  $\rho_k^v \geq \eta_2$  is now proved as in [5, Theorem 6.4.2] and uses (3.12), the inequality in (2.47), (2.48), (2.12), part (i) of Lemma 3.3, (3.2), and Lemma 3.4. Finally, using this fact, (2.47), and (2.51), we have  $\delta_{k+1}^v \geq \delta_k^v$ .  $\square$

Lemma 3.8 allows us to provide uniform lower bounds on the trust-region radii for iterations that have not resulted in (approximate) KKT points.

**Lemma 3.9.** *If there exists a constant  $\epsilon_f > 0$  that satisfies*

$$\pi_k^f \geq \epsilon_f \text{ for all } k \in \mathcal{F}, \quad (3.13)$$

*then*

$$\delta_k^f \geq \epsilon_{\mathcal{F}} \text{ for some } \epsilon_{\mathcal{F}} > 0 \text{ for all } k. \quad (3.14)$$

*Proof.* The statement follows from part (i) of Lemma 3.8, (2.57), the fact that  $\mathcal{F} \subseteq \mathcal{T} \setminus \mathcal{T}_0$ , and the fact that  $\delta_{k+1}^f \leftarrow \delta_k^f$  for  $k \notin \mathcal{F}$ .  $\square$

**Lemma 3.10.** *There exist constants  $\{\kappa_{\Delta c3}, \kappa_{\Delta c4}\} \subset (0, 1)$  such that*

$$\delta_k^v \geq \min\{\kappa_{\Delta c3}, \kappa_{\Delta c4} \pi_k^v\} \text{ for all } k. \quad (3.15)$$

Therefore, if there exists some  $\epsilon_\theta > 0$  such that

$$\pi_k^v \geq \epsilon_\theta \text{ for all } k \in \mathcal{V}, \quad (3.16)$$

then

$$\delta_k^v \geq \min\{\kappa_{\Delta c3}, \kappa_{\Delta c4}\epsilon_\theta\} =: \epsilon_C \text{ for all } k. \quad (3.17)$$

*Proof.* With  $\gamma_1 \in (0, 1)$  defined for (2.43), we prove by induction that

$$\delta_k^v \geq \gamma_1 \min\{\delta_0^v, \kappa_{\Delta c1}, \kappa_{\delta vv}\pi_k^v, \kappa_{\Delta c2}\pi_k^v\} \text{ for all } k. \quad (3.18)$$

This inequality holds trivially for  $k = 0$ , so supposing that it holds for iteration  $k$ , we must prove that it again holds for iteration  $k + 1$ .

First, suppose that  $k \in \mathcal{Y} \cup (\mathcal{F} \setminus \mathcal{S}_f)$ . Since  $\delta_{k+1}^v \leftarrow \delta_k^v$  and  $(x_{k+1}, s_{k+1}) \leftarrow (x_k, s_k)$  for such iterations, we conclude that (3.18) holds at iteration  $k + 1$ . Second, if  $k \in \mathcal{S}_f$ , then (2.41) and  $\gamma_1 \in (0, 1)$  ensure that (3.18) holds at iteration  $k + 1$ . Third, if  $k \in \mathcal{S}_v$ , then (2.51) ensures that (3.18) holds at iteration  $k + 1$ . Finally, suppose that  $k \in \mathcal{V} \setminus \mathcal{S}_v$ . In this case, the second part of Lemma 3.8 implies that  $\delta_k^v > \min\{\kappa_{\Delta c1}, \kappa_{\Delta c2}\pi_k^v\}$ . This may then be combined with (2.54) and the fact that  $(x_{k+1}, s_{k+1}) \leftarrow (x_k, s_k)$  to deduce that  $\delta_{k+1}^v \geq \gamma_1 \min\{\kappa_{\Delta c1}, \kappa_{\Delta c2}\pi_k^v\}$  so that (3.18) again holds at iteration  $k + 1$ . We therefore obtain that (3.15) holds for all  $k$  with  $\kappa_{\Delta c3} := \gamma_1 \min\{\delta_0^v, \kappa_{\Delta c1}\}$  and  $\kappa_{\Delta c4} := \gamma_1 \min\{\kappa_{\delta vv}, \kappa_{\Delta c2}\}$ . The bound (3.17) then directly follows from (3.15), (3.16), and the observation that  $\delta_k^v$  is never decreased for  $k \in \mathcal{Y} \cup \mathcal{F}$ .  $\square$

We now give our first main result, namely that if there are finitely many successful iterations, then Algorithm 1 terminates finitely.

**Theorem 3.11.** *If  $|\mathcal{S}| < \infty$ , then Algorithm 1 terminates finitely.*

*Proof.* To derive a contradiction, suppose that Algorithm 1 does not terminate finitely. It then follows from the fact that  $|\mathcal{S}| < \infty$ , (2.35), (2.42), (2.45), (2.53), and (2.55) that for some  $x_* \in \mathbb{R}^N$ ,  $s_* \in \mathbb{R}^M$ , and  $\{v_*, v_*^{\max}, \pi_*^v\} \subset \mathbb{R}$  there exists an integer  $k_s$  such that

$$(x_k, s_k) = (x_*, s_*), \quad v_k = v_*, \quad v_k^{\max} = v_*^{\max}, \quad \pi_k^v = \pi_*^v, \quad \text{and } k \notin \mathcal{S} \text{ for all } k \geq k_s. \quad (3.19)$$

Also, the fact that  $|\mathcal{S}| < \infty$  and Lemma 2.7 ensure that  $s_* > 0$ .

Suppose that  $|\mathcal{V}| = \infty$ . Then, by (3.19) (in particular, the fact that  $k \notin \mathcal{S}$  for  $k \geq k_s$ ), it follows that (2.54) would set  $\delta_{k+1}^v \leq \gamma_2 \delta_k^v$  for all  $k \in \mathcal{V}$  with  $k \geq k_s$ . Combining this with the fact that (2.35) and (2.44) would set  $\delta_{k+1}^v \leftarrow \delta_k^v$  for all  $k \in \mathcal{Y} \cup \mathcal{F}$  with  $k \geq k_s$ , it follows that  $\{\delta_k^v\} \rightarrow 0$ . We also have from part (ii) of Lemma 3.8 and the facts that  $|\mathcal{V}| = \infty$  and  $|\mathcal{S}| < \infty$  that we must have  $\lim_{k \in \mathcal{V}} \pi_k^v = 0$ , so in (3.19) we must have  $\pi_*^v = 0$ . If  $v_* > 0$ , then this implies that for  $k = k_s$  the algorithm would terminate finitely in Step 8, which contradicts the supposition of the proof. Thus, we must have that  $v_* = 0$ . Since  $v_* = \pi_*^v = 0$ , it follows from the conditions of Step 9 that  $n_k = 0$  for all  $k \geq k_s$ . This implies that (2.19) will be satisfied for all  $k \geq k_s$ , which in turn implies by Step 15 of the algorithm that  $y_k, r_k, \pi_k^f$ , and  $\chi_k^f$  will be computed to satisfy (2.25a), (2.25b), or (2.25c). If (2.25a) were to hold, then the algorithm would terminate finitely, a contradiction. Thus, we know that (2.25a) does not hold for all  $k \geq k_s$ , which combined with the fact that  $v_* = 0$  implies that  $\pi_k^f > \epsilon_\pi > 0$  for all  $k \geq k_s$ . It follows from this fact, part (i) of Lemma 3.8, the fact that  $\{\delta_k^v\} \rightarrow 0$ , and the fact that  $|\mathcal{S}| < \infty$  that we must have  $|\mathcal{F}| < \infty$ . Next, it follows from the facts that  $v_* = 0$  and  $\{\delta_k^v\} \rightarrow 0$ , Lemma 3.4, and (3.19) that (2.36) will be satisfied for all sufficiently large  $k$ . We may also deduce from the fact that  $n_k = 0$  for all  $k \geq k_s$  that (2.31) holds for all  $k \geq k_s$ . Since we have shown that  $|\mathcal{F}| < \infty$  and that both (2.31) and (2.36) hold for sufficiently large  $k$ , we may conclude that  $t_k = 0$  for all sufficiently large  $k$ . Therefore, since we have shown that  $n_k = t_k = 0$  for all sufficiently large  $k$ , we have from part (vi) of Lemma 2.6 that  $k \in \mathcal{Y}$  for all sufficiently large  $k$ , which combined with part (vii) of Lemma 2.6

implies that  $\{\pi_k^f\} \rightarrow 0$ . However, this contradicts our earlier conclusion that  $\pi_k^f \geq \epsilon_\pi > 0$  for all  $k \geq k_s$ . Overall, we have shown that we cannot have  $|\mathcal{V}| = \infty$ , so we must have  $|\mathcal{V}| < \infty$ .

Next, suppose that  $|\mathcal{F}| < \infty$ . Combining this with the fact that  $|\mathcal{V}| < \infty$  ensures that  $k \in \mathcal{Y}$  for all sufficiently large  $k$ . It follows from this fact and part (vii) of Lemma 2.6 that  $\{\pi_k^f\} \rightarrow 0$ , and that  $y_k, r_k, \pi_k^f$ , and  $\chi_k^f$  will be computed to satisfy (2.25a), (2.25b), or (2.25c) for all sufficiently large  $k$ . During the computation of these quantities, (2.25a) can never be satisfied, since in that case the algorithm would terminate finitely, which is a contradiction. Hence, since (2.25a) is never satisfied and  $\{\pi_k^f\} \rightarrow 0$ , we may deduce that  $v_* > \epsilon_v > 0$ . It then follows that  $\pi_*^v > 0$ , or else for  $k = k_s$  the algorithm would terminate in Step 8, which again is a contradiction. Combining  $\pi_*^v > 0$  with (3.19), the fact that  $\{\pi_k^f\} \rightarrow 0$ , and (2.8) implies that  $k \in \mathcal{N}$  for all  $k$  sufficiently large. Thus it follows from part (i) of Lemma 2.6 that  $n_k \neq 0$ , which contradicts our earlier conclusion that  $k \in \mathcal{Y}$ . Overall, we cannot have  $|\mathcal{F}| < \infty$ , so we must have  $|\mathcal{F}| = \infty$ .

Since  $|\mathcal{F}| = \infty, |\mathcal{V}| < \infty$ , and  $|\mathcal{S}| < \infty$ , we know from (2.35) and (2.43) that  $\{\delta_k^f\} \rightarrow 0$ , which when combined with (2.57) and part (i) of Lemma 3.8 implies that  $\{\pi_k^f\}_{k \in \mathcal{F}} \rightarrow 0$ . Since (2.25a), (2.25b), or (2.25c) holds for  $k \in \mathcal{F} \subseteq \mathcal{T} \setminus \mathcal{T}_0$ , and since the algorithm does not terminate finitely, we know that (2.25a) must not hold for all  $k \in \mathcal{F}$ . Combining this with the fact that  $\{\pi_k^f\}_{k \in \mathcal{F}} \rightarrow 0$  implies that  $v_k > \epsilon_v$  for all sufficiently large  $k \in \mathcal{F}$ . Hence, since  $|\mathcal{F}| = \infty$ , it follows from (3.19) that  $v_* > \epsilon_v > 0$ . We then must conclude that  $\pi_*^v > 0$ , or else for  $k = k_s$  the algorithm would terminate finitely in Step 8, which is a contradiction. Since  $\{\pi_k^f\}_{k \in \mathcal{F}} \rightarrow 0$ , it follows that (2.25b) will be satisfied for all sufficiently large  $k \in \mathcal{F}$ , which implies that  $t_k = 0$  and thus  $k \notin \mathcal{F}$ , which once more is a contradiction.

Overall, in all cases, we have reached contradictions of our supposition that Algorithm 1 does not terminate finitely, so the result is proved.  $\square$

We next prove a technical result about the violation decrease following a successful  $v$ -iteration.

**Lemma 3.12.** *There exist constants  $\kappa_{v\pi_1}, \kappa_{v\pi_2} > 0$  such that if  $k \in \mathcal{S}_v$ , then*

$$v_{k+1} \leq v_k - \pi_k^v \min(\kappa_{v\pi_1}, \kappa_{v\pi_2} \pi_k^v), \quad \text{and} \quad (3.20a)$$

$$v_{k+1}^{\max} \leq \max\{\kappa_{t1} v_k^{\max}, v_k - (1 - \kappa_{t2}) \pi_k^v \min(\kappa_{v\pi_1}, \kappa_{v\pi_2} \pi_k^v)\}, \quad (3.20b)$$

while (2.30) does not hold.

*Proof.* Let  $k \in \mathcal{S}_v$ , which by the definition of  $\mathcal{S}_v$  means that (2.47) holds. In particular, we have  $n_k \neq 0$ . Combining this fact with part (ii) of Lemma 2.6 means that  $k \in \mathcal{S}_v \cap \mathcal{N}$ . It follows from this fact, (2.49), (2.48), (2.47), (2.12), part (i) of Lemma 3.3, Lemmas 3.10 (specifically (3.15)) and 3.2 that there exist constants  $\kappa_{v\pi_1}, \kappa_{v\pi_2} > 0$  such that (3.20a) holds, which in turn implies with (2.52) that (3.20b) holds. Note that (3.20a) and Lemma 2.9 imply that (2.36) holds.

We now prove that (2.30) does not hold. To reach a contradiction, suppose that (2.30) holds, which immediately implies that  $t_k \neq 0$ . Part (iv) of Lemma 2.6 then implies that  $k \in \mathcal{T} \setminus \mathcal{T}_0$ , which combined with the fact that (2.30) is assumed to hold shows that (2.31) holds. Thus all the conditions of an  $f$ -iteration are satisfied so that  $k \in \mathcal{F}$ , which, since  $\mathcal{V} \cap \mathcal{F} = \emptyset$ , contradicts the fact that  $k \in \mathcal{S}_v \subseteq \mathcal{V}$ .  $\square$

We now show that if there are infinitely many iterations, then the  $v$ -criticality measure  $\pi_k^v$  converges to zero along a subsequence.

**Lemma 3.13.** *If Algorithm 1 does not terminate finitely, then*

$$0 = \begin{cases} \lim_{k \in \mathcal{S}_v} \pi_k^v & \text{if } |\mathcal{S}_v| = \infty, \\ \liminf_{k \in \mathcal{S}_f} \pi_k^v & \text{if } |\mathcal{S}_v| < \infty. \end{cases} \quad (3.21)$$

*Proof.* Lemma 2.9 shows that  $\{v_k^{\max}\}$  is monotonically decreasing and bounded below by zero. Therefore, if  $|\mathcal{S}_v| = \infty$  and the update (2.52) sets  $v_{k+1}^{\max} \leq \kappa_{t1} v_k^{\max}$  infinitely often, then  $\{v_k^{\max}\} \rightarrow 0$ . This would

imply with Lemma 2.9 that  $\{v_k\} \rightarrow 0$ , which in turn would imply with Assumptions 1.1 and 3.1 and Lemma 3.2 that  $\{\pi_k^v\} \rightarrow 0$  so that (3.21) holds in this case. Whereas, if  $|\mathcal{S}_v| = \infty$  and the update (2.52) sets  $v_{k+1}^{\max} > \kappa_{t1} v_k^{\max}$  for all sufficiently large  $k$ , then by Lemma 3.12 we have  $v_{k+1}^{\max} \leq v_k - (1 - \kappa_{t2}) \pi_k^v \min(\kappa_{v\pi1}, \kappa_{v\pi2} \pi_k^v)$  for  $k \in \mathcal{S}_v$ , which implies  $\{\pi_k^v\}_{k \in \mathcal{S}_v} \rightarrow 0$ , and again we have (3.21).

It remains to consider when  $|\mathcal{S}_v| < \infty$ , in which case, for some constant  $v_\infty^{\max} > 0$ , we have  $v_k^{\max} = v_\infty^{\max}$  for all sufficiently large  $k$ , since  $v_k^{\max}$  is only decreased for  $k \in \mathcal{S}_v$ . By Theorem 3.11, the conditions of this lemma, and the fact that  $|\mathcal{S}_v| < \infty$ , it follows that  $|\mathcal{S}_f| = \infty$ . Now, to derive a contradiction, suppose that there is a constant  $\pi_{\min}^v > 0$  such that

$$\pi_k^v \geq \pi_{\min}^v > 0 \quad \text{for all sufficiently large } k. \quad (3.22)$$

Since  $|\mathcal{S}_v| < \infty$ , we know from (2.35) for  $k \in \mathcal{V}$ , from (2.38) and (2.42) for  $k \in \mathcal{F}$ , from (2.53) for  $k \in \mathcal{V} \setminus \mathcal{S}_v$ , and the fact that the slack reset only possibly decreases the barrier function that  $\{f(x_k, s_k)\}$  is monotonically decreasing. Moreover, it follows from Assumptions 1.1 and 3.1 and Lemma 3.2 that  $\{f(x_k, s_k)\}$  is bounded below, so overall we have that  $\{f(x_k, s_k)\} \rightarrow f_{\text{low}}$  for some  $f_{\text{low}} > -\infty$ . It follows from this fact, the fact that  $|\mathcal{S}_f| = \infty$ , (2.37), (2.38), (2.31) (which holds for  $k \in \mathcal{F}$ ), (2.29a)/(2.34a), and part (ii) of Lemma 3.3 that  $\lim_{k \in \mathcal{S}_f} \min\{\pi_k^f, \delta_k^f\} = 0$ . Suppose that for some infinite index set  $\mathcal{K}_1 \subseteq \mathcal{S}_f$  and scalar  $\pi_{\min}^f > 0$  we have  $\pi_k^f \geq \pi_{\min}^f$  for all  $k \in \mathcal{K}_1$ . It follows that  $\{\delta_k^f\}_{k \in \mathcal{K}_1} \rightarrow 0$ . However, from part (ii) of Lemma 3.8, the fact that  $|\mathcal{S}_v| < \infty$ , and (3.22), it follows that  $\{\delta_k^v\}_{k \in \mathcal{V}}$  is bounded away from zero. In fact, since  $\delta_{k+1}^v \leftarrow \delta_k^v$  for  $k \notin \mathcal{V}$ , we conclude that  $\{\delta_k^v\}$  is bounded away from zero (for all  $k$ ). Combining this with the facts that  $\{\delta_k^f\}_{k \in \mathcal{K}_1} \rightarrow 0$  and  $v_k^{\max} = v_\infty^{\max} > 0$  for all sufficiently large  $k$  implies that  $\{\delta_k^f\}_{k \in \mathcal{K}_1} \rightarrow 0$ . It then follows from Lemma 3.9 that there exists an infinite index set  $\mathcal{K}_2 \subseteq \mathcal{F}$  such that  $\{\pi_k^f\}_{k \in \mathcal{K}_2} \rightarrow 0$ . Since  $\mathcal{K}_2 \subseteq \mathcal{F} \subseteq \mathcal{T} \setminus \mathcal{T}_0$ , we know that (2.25a), (2.25b), or (2.25c) is satisfied for all  $k \in \mathcal{K}_2$ . However, we also know that (2.25a) can not be satisfied since Algorithm 1 is assumed not to terminate finitely. It does, however, follow from  $\{\pi_k^f\}_{k \in \mathcal{K}_2} \rightarrow 0$  and (3.22) that (2.25b) will be satisfied for all sufficiently large  $k \in \mathcal{K}_2$  so that  $t_k = 0$  for all sufficiently large  $k \in \mathcal{K}_2 \subseteq \mathcal{F} \subseteq \mathcal{T} \setminus \mathcal{T}_0$ , which is a contradiction. Thus, we conclude that the set  $\mathcal{K}_1$  cannot exist, so  $\{\pi_k^f\} \rightarrow 0$ . It follows from this fact, (3.22), the fact that (2.25a), (2.25b), or (2.25c) is satisfied for all  $k \in \mathcal{F} \subseteq \mathcal{T} \setminus \mathcal{T}_0$ , and since the algorithm does not terminate finitely that (2.25b) will be satisfied (and hence  $t_k = 0$ ) for all sufficiently large  $k \in \mathcal{F} \subseteq \mathcal{T} \setminus \mathcal{T}_0$ , which again is a contradiction. Thus, our supposition that (3.22) held must be incorrect and therefore there is a subsequence  $\mathcal{K}$  such that  $\lim_{k \in \mathcal{K}} \pi_k^v = 0$ . Moreover, since  $|\mathcal{S}_v| < \infty$  and  $|\mathcal{S}_f| = \infty$ , we may conclude that (3.21) must hold.  $\square$

To proceed further, we define the active and inactive slack variable sets

$$\mathcal{A}(s) = \{i \in \{1, 2, \dots, M\} : [s]_i = 0\} \quad \text{and} \quad \mathcal{I}(s) = \{1, 2, \dots, M\} \setminus \mathcal{A}(s), \quad (3.23)$$

at  $s \in \mathbb{R}^M$ , and denote these sets by

$$\mathcal{A}_* := \mathcal{A}(s_*) \quad \text{and} \quad \mathcal{I}_* := \mathcal{I}(s_*)$$

at a point  $s_*$ . Armed with these definitions, we make the following assumption throughout the rest of our analysis.

**Assumption 3.2.** *If Algorithm 1 does not terminate finitely and  $(x_*, s_*)$  is a limit point of  $\{(x_k, s_k)\}$ , then either  $\mathcal{A}_* = \emptyset$  or  $J_{\mathcal{A}_*}(x_*)$  has full row rank, i.e.,  $J(x_*, s_*)P_*$  with  $P_* := \text{diag}(I, S_*)$  has full row rank.*

**Lemma 3.14.** *If Algorithm 1 does not terminate finitely and  $\mathcal{K}$  is an infinite index set such that  $\{\pi_k^v\}_{k \in \mathcal{K}} \rightarrow 0$ , then for an arbitrary limit point  $(x_*, s_*)$  of  $\{(x_k, s_k)\}_{k \in \mathcal{K}}$  it follows that  $v(x_*, s_*) = 0$  with  $x_*$  feasible for (NP).*

*Proof.* Let us define the feasibility problem

$$\underset{x,s}{\text{minimize}} \quad v(x,s) \quad \text{subject to} \quad s \geq 0$$

for which we have the first-order KKT conditions

$$\min\{s, c(x,s)\} = 0 \quad \text{and} \quad J(x)^T c(x,s) = 0. \quad (3.24)$$

For an arbitrary limit point  $(x_*, s_*)$  of  $\{(x_k, s_k)\}_{k \in \mathcal{K}}$ , it follows from Lemma 2.7 and  $\{\pi_k^v\}_{k \in \mathcal{K}} \rightarrow 0$  that

$$s_* \geq 0, \quad c(x_*, s_*) \geq 0, \quad S_* c(x_*, s_*) = 0, \quad \text{and} \quad J(x_*)^T c(x_*, s_*) = 0. \quad (3.25)$$

In particular, using (3.23) and (3.25), we have

$$[s_*]_{\mathcal{I}_*} > 0 \quad \text{and} \quad c_{\mathcal{I}_*}(x_*) < c_{\mathcal{I}_*}(x_*, s_*) = 0; \quad (3.26a)$$

$$[s_*]_{\mathcal{A}_*} = 0 \quad \text{and} \quad c_{\mathcal{A}_*}(x_*) = c_{\mathcal{A}_*}(x_*, s_*) \geq 0. \quad (3.26b)$$

Hence, from (3.25) and (3.26), we have that  $(x_*, s_*)$  satisfies (3.24). Now, if  $\mathcal{A}_* = 0$ , then by (3.26a) we have that  $v(x_*, s_*) = 0$  and  $c(x_*) \leq 0$ , as desired. Otherwise, by (3.25) and (3.26a), we have

$$0 = J(x_*)^T c(x_*, s_*) = J_{\mathcal{A}}(x_*)^T c_{\mathcal{A}}(x_*, s_*) = J_{\mathcal{A}}(x_*)^T c_{\mathcal{A}}(x_*).$$

Under Assumption 3.2, we have that  $J_{\mathcal{A}}(x_*)$  has full row rank, so the above implies that  $0 = c_{\mathcal{A}}(x_*) = c_{\mathcal{A}}(x_*, s_*)$ . Combining this with (3.26a) again yields  $v(x_*, s_*) = 0$  and  $c(x_*) \leq 0$ , as desired.  $\square$

We now prove that if there are an infinite number of successful  $v$ -iterations, then feasibility is achieved at all limit points of the sequence of iterates computed by the algorithm.

**Lemma 3.15.** *If  $|\mathcal{S}_v| = \infty$ , then  $\{v_k^{\max}\} \rightarrow 0$ ,  $\{v_k\} \rightarrow 0$ ,  $\{\pi_k^v\} \rightarrow 0$ , and  $\{n_k\} \rightarrow 0$ .*

*Proof.* Lemma 2.9 shows that  $\{v_k^{\max}\}$  is monotonically decreasing and bounded below by zero. Then, as in the proof of Lemma 3.13, we have that if the update (2.52) sets  $v_{k+1}^{\max} \leq \kappa_{t_1} v_k^{\max}$  infinitely often, then  $\{v_k^{\max}\} \rightarrow 0$ ,  $\{v_k\} \rightarrow 0$ , and  $\{\pi_k^v\} \rightarrow 0$ . It then follows from this fact, (2.11), and Lemma 3.2 that  $\{n_k\} \rightarrow 0$ .

Thus, all that remains is to consider the case when the update (2.52) sets  $v_{k+1}^{\max} > \kappa_{t_1} v_k^{\max}$  for all large  $k$ . As in the proof of Lemma 3.13, this implies that  $\{\pi_k^v\}_{k \in \mathcal{S}_v} \rightarrow 0$ . This, along with Lemma 3.14, Assumption 3.1, and the boundedness of  $\{s_k\}$  stated in Lemma 3.2 implies that there exists an infinite index set  $\mathcal{K} \subseteq \mathcal{S}_v$  such that  $\{v_k\}_{k \in \mathcal{K}} \rightarrow 0$ . We then have from Lemma 3.12 (in particular, (3.20b)) that  $\{v_k^{\max}\}_{k \in \mathcal{K}} \rightarrow 0$ , which means that  $\{v_k^{\max}\} \rightarrow 0$  and hence  $\{v_k\} \rightarrow 0$  because of Lemma 2.9. Combining this with Assumptions 1.1 and 3.1 and Lemma 3.2, we thus have  $\{\pi_k^v\} \rightarrow 0$ . It follows from this fact, (2.11), and Lemma 3.2 that  $\{n_k\} \rightarrow 0$ .  $\square$

We next prove a result illustrating the importance of the sequence  $\{\pi_k^f\}$ . In particular, the result establishes that under Assumption 3.2,  $\pi_k^f$  is a valid criticality measure for (1.1).

**Lemma 3.16.** *If  $\mathcal{K}$  is any subsequence and  $(x_*, s_*)$  is any point such that  $\lim_{k \in \mathcal{K}} (x_k, s_k) = (x_*, s_*)$  with  $v(x_*, s_*) = 0$  and  $\lim_{k \in \mathcal{K}} \pi_k^f = 0$ , then  $\lim_{k \in \mathcal{K}} y_k = y_*$  where  $(x_*, s_*, y_*)$  is a KKT point for problem (1.1).*

*Proof.* Since  $v(x^*, s^*) = 0$ , it follows that  $\lim_{k \in \mathcal{K}} c(x_k, s_k) = c(x_*, s_*) = 0$ , which, when combined with Lemma 3.2, proves that  $\lim_{k \in \mathcal{K}} \pi_k^v = 0$ . Thus, it follows from (2.11) and Lemma 3.2 that

$$\lim_{k \in \mathcal{K}} n_k = 0. \quad (3.27)$$

Recall the notation  $\mathcal{I}_* = \mathcal{I}(s_*)$  and observe that

$$\begin{aligned} 0 &= \lim_{k \in \mathcal{K}} \pi_k^f = \lim_{k \in \mathcal{K}} \left\| P_k \left( \nabla m_k^f(n_k) + J(x_k, s_k)^T y_k \right) \right\|_2 \\ &= \lim_{k \in \mathcal{K}} \left\| \begin{pmatrix} g(x_k) + \nabla_{xx} \mathcal{L}(x_k, y_k^B) n_k^x + J(x_k)^T y_k \\ -\mu e + S_k D_k n_k^s + S_k y_k \end{pmatrix} \right\|_2 \end{aligned} \quad (3.28)$$

$$= \lim_{k \in \mathcal{K}} \left\| \begin{pmatrix} g(x_k) + \nabla_{xx} \mathcal{L}(x_k, y_k^B) n_k^x + J(x_k)^T y_k \\ [-\mu e + S_k D_k n_k^s + S_k y_k]_{\mathcal{A}_*} \\ [-\mu e + S_k D_k n_k^s + S_k y_k]_{\mathcal{I}_*} \end{pmatrix} \right\|_2. \quad (3.29)$$

Using (3.29) (specifically the third row of equations inside the norm) with  $\lim_{k \in \mathcal{K}} (x_k, s_k) = (x_*, s_*)$ ,  $[s_*]_{\mathcal{I}_*} > 0$ , (2.18), Lemma 3.2 and (3.27) shows that

$$\lim_{k \in \mathcal{K}} [y_k]_{\mathcal{I}_*} = [\mu S_*^{-1} e]_{\mathcal{I}_*} =: [y_*]_{\mathcal{I}_*}.$$

It then follows from (3.29) (specifically the first row of equations inside the norm),  $\lim_{k \in \mathcal{K}} (x_k, s_k) = (x_*, s_*)$ , (2.18), (2.17), Lemma 3.1, (3.27), and the full row rank of  $J_{\mathcal{A}_*}(x_*)$  (see Assumption 3.2) that

$$\lim_{k \in \mathcal{K}} [y_k]_{\mathcal{A}_*} = -[J_{\mathcal{A}_*}(x_*) J_{\mathcal{A}_*}(x_*)^T]^{-1} J_{\mathcal{A}_*}(x_*) \left( g(x_*) + J_{\mathcal{I}_*}(x_*)^T [y_*]_{\mathcal{I}_*} \right) =: [y_*]_{\mathcal{A}_*}.$$

We have shown that the dual sequence converges along  $\mathcal{K}$ , i.e., that  $\lim_{k \in \mathcal{K}} y_k = y_*$  for some  $y_* \in \mathbb{R}^M$ . Combining this with (3.28),  $\lim_{k \in \mathcal{K}} (x_k, s_k) = (x_*, s_*)$ , (2.18), (2.17), Lemma 3.1, and (3.27) proves that

$$g(x_*) + J(x_*)^T y_* = 0 \quad \text{and} \quad S_* y_* = \mu e. \quad (3.30)$$

Note that it follows from (3.30), Lemma 2.7, and  $\mu > 0$  that  $(s_*, y_*) > 0$ . Combining this with (3.30) and  $v(x_*, s_*) = 0$  proves that  $(x_*, y_*, s_*)$  is a KKT point for problem (1.1).  $\square$

Lemmas 3.14 and 3.16 prove that under Assumption 3.2, we may obtain a first-order KKT point for the barrier subproblem (1.1) with any subsequence over which  $\pi_k^v \rightarrow 0$  and  $\pi_k^f \rightarrow 0$ . Now, to prove that such a sequence will exist, we make the following assumption (stronger than Assumption 3.2) for the remainder of our analysis. The assumption states that at any nearly feasible point, the singular values of a scaled constraint Jacobian are bounded away from zero.

**Assumption 3.3.** *There exists a constant  $\kappa_c > 0$  independent of  $k$  such that if  $v_k \leq \kappa_c$ , then the smallest singular value of  $J(x_k, s_k) P_k$  is greater than  $\kappa_j$  for some constant  $\kappa_j > 0$  independent of  $k$ .*

We also define the following projection operator. Note that this operator is used for theoretical purposes only, i.e., computing such projections is unnecessary in an implementation of our algorithm.

**Definition 3.17.** *Let  $\text{Proj}_k(d)$  denote the orthogonal projection of  $d$  onto the range space of  $P_k J(x_k, s_k)^T$ .*

**Lemma 3.18.** *If  $k \in \mathcal{N} \cap \mathcal{D}$  and  $v_k \leq \kappa_c$ , then there exist constants  $\kappa_{R1}, \kappa_{R2} > 0$  such that*

$$\|\text{Proj}_k(P_k^{-1} d_k)\|_2 \leq \frac{1}{\kappa_j^2} \pi_k^v \quad \text{and} \quad \Delta m_k^{v,d} \geq \|\text{Proj}_k(P_k^{-1} d_k)\|_2 \min(\kappa_{R1}, \kappa_{R2}) \|\text{Proj}_k(P_k^{-1} d_k)\|_2. \quad (3.31)$$

*Proof.* Let  $k \in \mathcal{N} \cap \mathcal{D}$  and define  $m_k^P(d) := \|c(x_k, s_k) + J(x_k, s_k) P_k d\|_2^2$  and  $d_k^P := P_k^{-1} d_k$ . Then, it follows from the fact that  $J(x_k, s_k) P_k \text{Proj}_k(d_k^P) = J(x_k, s_k) P_k d_k^P$ , part (i) of Lemma 2.6, and (2.29d) that

$$\begin{aligned} m_k^P(\text{Proj}_k(d_k^P)) &= \|c(x_k, s_k) + J(x_k, s_k) P_k \text{Proj}_k(d_k^P)\|_2^2 = \|c(x_k, s_k) + J(x_k, s_k) P_k d_k^P\|_2^2 \\ &= m_k^v(d_k) < m_k^v(0) = m_k^P(0). \end{aligned} \quad (3.32)$$

We may also note that since  $v_k \leq \kappa_c$ , we have under Assumption 3.3 that the smallest eigenvalue of  $\nabla_{xx} m_k^v(0) = 2P_k^T J(x_k, s_k)^T J(x_k, s_k) P_k$  is bounded below by  $2\kappa_J^2 > 0$ . We may now use this fact, (3.32), and [5, Lemma 6.5.1] to conclude that

$$\|\text{Proj}_k(P_k^{-1}d_k)\|_2 = \|\text{Proj}_k(d_k^P)\|_2 \leq \frac{1}{\kappa_J^2} \pi_k^v,$$

which proves the first inequality in (3.31). It also follows from Lemma 3.4 and the fact that the orthogonal projection operator is nonexpansive that

$$\delta_k^v \geq \|P_k^{-1}d_k\|_2 \geq \|\text{Proj}_k(P_k^{-1}d_k)\|_2.$$

Combining this with  $k \in \mathcal{D}$ , part (ix) of Lemma 2.6, the inequality in (2.47), (2.12), part (i) of Lemma 3.3, and the first inequality in (3.31), we have that the second inequality in (3.31) holds.  $\square$

We now bound the size of the normal step along a certain subsequence of unsuccessful  $v$ -iterations.

**Lemma 3.19.** *If  $k \in (\mathcal{N} \cap \mathcal{V} \cap \mathcal{D}) \setminus \mathcal{S}_v$  and*

$$v_k \leq \min \left\{ \kappa_c, \left( \frac{\kappa_{\Delta c1}}{\kappa_{\Delta c2} \kappa_J} \right)^2, \left( \frac{1 - \kappa_{\text{fbn}}}{\kappa_{\Delta c2} \kappa_J} \right)^2 \right\}, \quad (3.33)$$

then, for some constants  $\{\kappa_{\text{cld}}, \kappa_{\text{sRn}}\} \subset (0, 1)$ , we have

$$m_k^v(d_k) \leq \kappa_{\text{cld}} v_k \quad \text{and} \quad \|\text{Proj}_k(P_k^{-1}d_k)\|_2 \geq \kappa_{\text{sRn}} \|P_k^{-1}n_k\|_2. \quad (3.34)$$

*Proof.* Consider  $k \in (\mathcal{N} \cap \mathcal{V} \cap \mathcal{D}) \setminus \mathcal{S}_v$  such that (3.33) holds. It follows from the fact that  $k \in \mathcal{N} \cap \mathcal{D}$ , part (ix) of Lemma 2.6, the inequality in (2.47), (2.12), part (i) of Lemma 3.3, and Assumption 3.3 that

$$\begin{aligned} m_k^v(d_k) &\leq m_k^v(0) - \kappa_{\text{cd}} \kappa_{\text{cn}} \pi_k^v \min \{ \pi_k^v, \delta_k^v, 1 - \kappa_{\text{fbn}} \} \\ &\leq m_k^v(0) - \kappa_{\text{cd}} \kappa_{\text{cn}} \kappa_J \|c(x_k, s_k)\|_2 \min \{ \kappa_J \|c(x_k, s_k)\|_2, \delta_k^v, 1 - \kappa_{\text{fbn}} \}. \end{aligned} \quad (3.35)$$

It also follows from part (ii) of Lemma 3.8, the fact that  $k \in \mathcal{V} \setminus \mathcal{S}_v$ , (3.33), and Assumption 3.3 that

$$\delta_k^v > \min \{ \kappa_{\Delta c1}, \kappa_{\Delta c2} \pi_k^v \} \geq \min \{ \kappa_{\Delta c1}, \kappa_{\Delta c2} \kappa_J \|c(x_k, s_k)\|_2 \} = \kappa_{\Delta c2} \kappa_J \|c(x_k, s_k)\|_2.$$

Substituting this into (3.35) ensures by (3.33) the existence of  $\kappa_{\text{cld}} \in (0, 1)$  independent of  $k$  such that

$$\begin{aligned} m_k^v(d_k) &\leq m_k^v(0) - \kappa_{\text{cd}} \kappa_{\text{cn}} \kappa_J \|c(x_k, s_k)\|_2 \min \{ \kappa_J \|c(x_k, s_k)\|_2, \kappa_{\Delta c2} \kappa_J \|c(x_k, s_k)\|_2, 1 - \kappa_{\text{fbn}} \} \\ &= m_k^v(0) - \kappa_{\text{cd}} \kappa_{\text{cn}} \kappa_J \|c(x_k, s_k)\|_2 \min \{ \kappa_J \|c(x_k, s_k)\|_2, \kappa_{\Delta c2} \kappa_J \|c(x_k, s_k)\|_2 \} \\ &= m_k^v(0) - \kappa_{\text{cd}} \kappa_{\text{cn}} \kappa_J \min \{ \kappa_J, \kappa_{\Delta c2} \kappa_J \} \|c(x_k, s_k)\|_2^2 \leq \kappa_{\text{cld}} v_k. \end{aligned}$$

This is the first desired result. Next, defining  $d_k^P := P_k^{-1}d_k$ , we may use the inequality above, the reverse triangle inequality, and the fact that  $J(x_k, s_k)P_k d_k^P = J(x_k, s_k)P_k \text{Proj}_k(d_k^P)$  to have

$$\begin{aligned} \|c(x_k, s_k)\|_2 - \|J(x_k, s_k)P_k \text{Proj}_k(d_k^P)\|_2 &\leq \|c(x_k, s_k) + J(x_k, s_k)P_k \text{Proj}_k(d_k^P)\|_2 \\ &= \|c(x_k, s_k) + J(x_k, s_k)P_k d_k^P\|_2 \\ &= \|c(x_k, s_k) + J(x_k, s_k)d_k\|_2 = \sqrt{m_k^v(d_k)} \\ &\leq \sqrt{\kappa_{\text{cld}} v_k} = \sqrt{\kappa_{\text{cld}}} \|c(x_k, s_k)\|_2. \end{aligned}$$

Combining the above with the fact that  $k \in \mathcal{N}$ , (2.5), and the Cauchy-Schwarz inequality then implies

$$\begin{aligned} \|P_k^{-1}n_k\|_2 &\leq \kappa_n \pi_k^v \leq \kappa_n \|P_k J(x_k, s_k)^T\|_2 \|c(x_k, s_k)\|_2 \\ &\leq \kappa_n \|P_k J(x_k, s_k)^T\|_2 \frac{\|J(x_k, s_k)P_k \text{Proj}_k(d_k^P)\|_2}{1 - \sqrt{\kappa_{\text{clid}}}} \\ &\leq \kappa_n \|P_k J(x_k, s_k)^T\|_2 \frac{\|J(x_k, s_k)P_k\|_2 \|\text{Proj}_k(d_k^P)\|_2}{1 - \sqrt{\kappa_{\text{clid}}}}. \end{aligned}$$

It then follows from the definition of  $d_k^P$ , Lemma 3.2, and the fact that  $\kappa_{\text{clid}} \in (0, 1)$  that for some  $\kappa_{\text{sRn}} \in (0, 1)$  independent of  $k$ , we have

$$\|\text{Proj}_k(P_k^{-1}d_k)\|_2 \geq \frac{1 - \sqrt{\kappa_{\text{clid}}}}{\kappa_n \|J(x_k, s_k)P_k\|_2^2} \|P_k^{-1}n_k\|_2 \geq \kappa_{\text{sRn}} \|P_k^{-1}n_k\|_2,$$

which is the second desired result.  $\square$

For our next set of results, given the parameter  $\epsilon > 0$ , we define the functions

$$\varsigma_{\text{tn}}(\epsilon) := \kappa_{\mathcal{V}\mathcal{S}} \max \left\{ 1, \frac{2\kappa_{\text{ub}}}{(1 - \kappa_{\delta})(\kappa_{\mathcal{V}\mathcal{S}} - 1)\kappa_{\text{ct}}(1 - \kappa_{\text{B}})\epsilon} \right\} \quad \text{and} \quad (3.36a)$$

$$\varsigma_{\delta}(\epsilon) := \min \left\{ 1, \frac{\epsilon}{1 - \kappa_{\text{B}}}, \frac{(1 - \kappa_{\text{fbt}})\kappa_{\text{bfn}}}{1 - \kappa_{\text{B}}} \right\}, \quad (3.36b)$$

where we have defined  $\kappa_{\mathcal{V}\mathcal{S}} > 1$  in (2.30),  $\kappa_{\text{ub}} \geq 1$  in Lemma 3.2,  $\kappa_{\delta} \in (0, 1)$  in (2.31),  $\kappa_{\text{ct}} \in (0, \frac{1}{2}]$  in part (ii) of Lemma 3.3,  $\kappa_{\text{B}} \in (0, 1)$  in (2.19),  $\kappa_{\text{c}} \in (0, 1)$  in Assumption 3.3,  $\kappa_{\text{fbt}} \in (0, 1)$  in (2.20), and  $\kappa_{\text{bfn}} \in (0, 1)$  in (2.5).

**Lemma 3.20.** *If there exists  $\epsilon > 0$  independent of  $k$  such that  $k \notin \mathcal{Y}$ ,*

$$\pi_k^f \geq \epsilon > 0, \quad (3.37a)$$

$$\min\{\delta_k^v, \delta_k^f\} \leq \varsigma_{\delta}(\epsilon), \quad \text{and} \quad (3.37b)$$

$$\|P_k^{-1}t_k\|_2 \geq \varsigma_{\text{tn}}(\epsilon) \|P_k^{-1}n_k\|_2, \quad (3.37c)$$

then  $t_k \neq 0$  and (2.31) holds.

*Proof.* Let  $k \notin \mathcal{Y}$  be such that (3.37) holds. If  $k \in \mathcal{F}$ , then the results follow by the definition of the index set  $\mathcal{F}$ . Thus, for the remainder of the proof, we may assume that  $k \in \mathcal{V}$ .

If  $n_k = 0$ , then  $t_k \neq 0$  (since otherwise we have  $k \in \mathcal{Y}$  by part (vi) of Lemma 2.6) and  $\Delta m_k^{f,d} = \Delta m_k^{f,t} \geq 0$ , meaning that (2.31) holds, which are the desired results. Otherwise, if  $n_k \neq 0$ , then since  $s_k > 0$  and  $P_k \succ 0$  for all  $k$  and (3.37c) holds, we have that  $t_k \neq 0$ , which implies that  $k \in \mathcal{T} \setminus \mathcal{T}_0$  and (2.19) holds. It then follows from the reverse triangle inequality, (3.37c), and (3.36a) that

$$\|P_k^{-1}d_k\|_2 \geq \|P_k^{-1}t_k\|_2 - \|P_k^{-1}n_k\|_2 = \left(1 - \frac{\|P_k^{-1}n_k\|_2}{\|P_k^{-1}t_k\|_2}\right) \|P_k^{-1}t_k\|_2 \geq \left(\frac{\kappa_{\mathcal{V}\mathcal{S}} - 1}{\kappa_{\mathcal{V}\mathcal{S}}}\right) \|P_k^{-1}t_k\|_2. \quad (3.38)$$

We also have that

$$-\Delta m_k^{f,n} = \nabla f(x_k, s_k)^T n_k + \frac{1}{2} n_k^T G_k n_k = (P_k \nabla f(x_k, s_k))^T P_k^{-1} n_k + \frac{1}{2} (P_k^{-1} n_k)^T P_k G_k P_k (P_k^{-1} n_k). \quad (3.39)$$

Using the triangle and Cauchy-Schwarz inequalities, Lemma 3.2, and the fact that (2.19) and (3.37b) imply  $\|P_k^{-1}n_k\|_2 \leq \min\{\delta_k^v, \delta_k^f\} \leq 1$ , we then have

$$|\Delta m_k^{f,n}| \leq \kappa_{\text{ub}} \left( \|P_k^{-1}n_k\|_2 + \frac{1}{2} \|P_k^{-1}n_k\|_2^2 \right) \leq 2\kappa_{\text{ub}} \|P_k^{-1}n_k\|_2. \quad (3.40)$$

Moreover, it follows from the fact that  $k \in \mathcal{T} \setminus \mathcal{T}_0$ , part (ii) of Lemma 3.3, (3.37a), (2.57), and (3.37b) that

$$\Delta m_k^{f,t} \geq \kappa_{\text{ct}} \epsilon \min \left\{ \epsilon, (1 - \kappa_{\text{B}}) \delta_k^t, (1 - \kappa_{\text{fbt}}) \kappa_{\text{fbb}} \right\} = \kappa_{\text{ct}} \epsilon (1 - \kappa_{\text{B}}) \delta_k^t.$$

Combining this with (3.40), the fact that  $k \in \mathcal{T} \setminus \mathcal{T}_0$ , Lemma 3.4, (3.38), and (3.37c) yields

$$\frac{|\Delta m_k^{f,n}|}{\Delta m_k^{f,t}} \leq \frac{2\kappa_{\text{ub}} \|P_k^{-1} n_k\|_2}{\kappa_{\text{ct}} \epsilon (1 - \kappa_{\text{B}}) \delta_k^t} \leq \frac{2\kappa_{\text{ub}} \|P_k^{-1} n_k\|_2}{\kappa_{\text{ct}} \epsilon (1 - \kappa_{\text{B}}) \|P_k^{-1} d_k\|_2} \leq \frac{2\kappa_{\text{ub}} \kappa_{\text{vS}}}{\kappa_{\text{ct}} \epsilon (1 - \kappa_{\text{B}}) (\kappa_{\text{vS}} - 1)} \frac{\|P_k^{-1} n_k\|_2}{\|P_k^{-1} t_k\|_2} \leq 1 - \kappa_{\delta}.$$

Hence, (2.31) holds, which completes the proof.  $\square$

We next prove that at nearly feasible points, certain  $v$ -iterates are guaranteed to be successful.

**Lemma 3.21.** *If there exists  $\epsilon > 0$  independent of  $k$  such that  $k \in \mathcal{V} \cap \mathcal{D}$ ,*

$$\|P_k^{-1} t_k\|_2 \leq \varsigma_{\text{tn}}(\epsilon) \|P_k^{-1} n_k\|_2, \quad (3.41)$$

and

$$v_k \leq \min \left\{ \kappa_{\text{c}}, \left( \frac{\kappa_{\Delta \text{c}1}}{\kappa_{\Delta \text{c}2} \kappa_{\text{J}}} \right)^2, \left( \frac{(1 - \kappa_{\text{fbb}})}{\kappa_{\Delta \text{c}2} \kappa_{\text{J}}} \right)^2, \left( \frac{\kappa_{\text{R}1}}{\kappa_{\text{R}2} \kappa_{\text{sRn}} \kappa_{\text{n}} \kappa_{\text{ub}}} \right)^2, \right. \\ \left. \left( \frac{\kappa_{\text{sRn}}^2 \kappa_{\text{R}2} (1 - \eta_1)}{(1 + \varsigma_{\text{tn}}(\epsilon))^2 [\kappa_{\text{v}1} (1 + \varsigma_{\text{tn}}(\epsilon)) \kappa_{\text{n}} \kappa_{\text{ub}} + \kappa_{\text{v}2}]} \right)^2 \right\}, \quad (3.42)$$

then  $k \in \mathcal{S}_v$  and  $\delta_{k+1}^v \geq \delta_k^v$ .

*Proof.* Consider  $k \in \mathcal{V} \cap \mathcal{D}$  such that (3.41) and (3.42) hold. If  $n_k = 0$ , then (3.41) implies that  $t_k = 0$ , which in turn implies by part (vi) of Lemma 2.6 that  $k \in \mathcal{Y}$ . However, this contradicts the supposition that  $k \in \mathcal{V}$ , so we must in fact have  $n_k \neq 0$ . In this case, part (ii) of Lemma 2.6 ensures that  $k \in \mathcal{N}$ , so that overall we have  $k \in \mathcal{N} \cap \mathcal{V} \cap \mathcal{D}$ .

To obtain a contradiction, suppose that  $k \notin \mathcal{S}_v$ , so that overall we have  $k \in (\mathcal{N} \cap \mathcal{V} \cap \mathcal{D}) \setminus \mathcal{S}_v$ . This and the bound (3.42) implies that the results of Lemmas 3.18 and 3.19 hold, i.e., that (3.31) and (3.34) hold. Moreover, the fact that  $k \in \mathcal{D}$  and part (ix) of Lemma 2.6 imply that the inequality in (2.47) holds. Using this fact, our conclusion that  $n_k \neq 0$ , and the fact that  $k \in \mathcal{V} \setminus \mathcal{S}_v$ , it follows from (2.53) that  $\rho_k^v < \eta_1$ . However, since (3.31) and (3.34) hold,

$$\Delta m_k^{v,d} \geq \|\text{Proj}_k(P_k^{-1} d_k)\|_2 \min(\kappa_{\text{R}1}, \kappa_{\text{R}2} \|\text{Proj}_k(P_k^{-1} d_k)\|_2) \geq \kappa_{\text{sRn}} \|P_k^{-1} n_k\|_2 \min(\kappa_{\text{R}1}, \kappa_{\text{R}2} \kappa_{\text{sRn}} \|P_k^{-1} n_k\|_2).$$

But it follows from (2.11), Lemma 3.2 and (3.42) that

$$\kappa_{\text{R}2} \kappa_{\text{sRn}} \|P_k^{-1} n_k\|_2 \leq \kappa_{\text{R}2} \kappa_{\text{sRn}} \kappa_{\text{n}} \pi_k^v \leq \kappa_{\text{R}2} \kappa_{\text{sRn}} \kappa_{\text{n}} \kappa_{\text{ub}} \|c(x_k, s_k)\|_2 \leq \kappa_{\text{R}2} \kappa_{\text{sRn}} \kappa_{\text{n}} \kappa_{\text{ub}} \sqrt{v_k} \leq \kappa_{\text{R}1}$$

and therefore

$$\Delta m_k^{v,d} \geq \kappa_{\text{sRn}}^2 \kappa_{\text{R}2} \|P_k^{-1} n_k\|_2^2. \quad (3.43)$$

Furthermore by (2.48), (3.3), (3.43), the triangle inequality, (3.41), (2.11), the Cauchy-Schwarz inequal-

ity, Lemma 3.2, and (3.42), we have that

$$\begin{aligned}
|\rho_k^v - 1| &= \left| \frac{v(x_k + d_k^x, s_k + d_k^s) - m_k^v(d_k)}{\Delta m_k^{v,d}} \right| \\
&\leq \frac{\|P_k^{-1}d_k\|_2^2}{\kappa_{sRn}^2 \kappa_{R2} \|P_k^{-1}n_k\|_2^2} (\kappa_{v1} \|P_k^{-1}d_k\|_2 + \kappa_{v2} \|c(x_k, s_k)\|_2) \\
&\leq \frac{(1 + \varsigma_{tn}(\epsilon))^2}{\kappa_{sRn}^2 \kappa_{R2}} (\kappa_{v1}(1 + \varsigma_{tn}(\epsilon)) \|P_k^{-1}n_k\|_2 + \kappa_{v2} \|c(x_k, s_k)\|_2) \\
&\leq \frac{(1 + \varsigma_{tn}(\epsilon))^2}{\kappa_{sRn}^2 \kappa_{R2}} (\kappa_{v1}(1 + \varsigma_{tn}(\epsilon)) \kappa_n \|P_k J(x_k, s_k)^T\|_2 + \kappa_{v2}) \|c(x_k, s_k)\|_2 \\
&\leq \frac{(1 + \varsigma_{tn}(\epsilon))^2}{\kappa_{sRn}^2 \kappa_{R2}} (\kappa_{v1}(1 + \varsigma_{tn}(\epsilon)) \kappa_n \kappa_{ub} + \kappa_{v2}) \|c(x_k, s_k)\|_2 \leq 1 - \eta_1,
\end{aligned}$$

which implies that  $\rho_k^v \geq \eta_1$ , which is a contradiction. Thus, we must conclude that  $k \in \mathcal{S}_v$ . The fact that  $\delta_{k+1}^v \geq \delta_k^v$  now follows from the fact that  $k \in \mathcal{S}_v$  and (2.51).  $\square$

We now prove that our algorithm terminates finitely if there are finitely many successful  $v$ -iterations.

**Lemma 3.22.** *If  $|\mathcal{S}_v| < \infty$ , then Algorithm 1 terminates finitely.*

*Proof.* We prove the result by contradiction, and so suppose that  $|\mathcal{S}_v| < \infty$ , but that Algorithm 1 does not terminate finitely. It then follows from Theorem 3.11 that  $|\mathcal{S}| = \infty$ , which when combined with the fact that  $|\mathcal{S}_v| < \infty$  implies that  $|\mathcal{S}_f| = \infty$ ; i.e., it follows that there are an infinite number of successful iterations, and all belong to  $\mathcal{S}_f$  for all sufficiently large  $k$ . We may also deduce from these facts—and since the barrier function is decreased for  $k \in \mathcal{S}_f$  and the slack reset only possibly decreases the barrier function—that the sequence  $\{f(x_k, s_k)\}$  is monotonically decreasing for sufficiently large  $k$ . Moreover, since  $v_{k+1}^{\max} \leftarrow v_k^{\max}$  for all  $k \notin \mathcal{S}_v$  and  $|\mathcal{S}_v| < \infty$ , we have that there exists a constant  $v_\infty^{\max} > 0$  such that

$$v_k^{\max} = v_\infty^{\max} > 0 \text{ for all sufficiently large } k. \quad (3.44)$$

We complete the proof by considering two cases depending on whether, for some  $\epsilon_f > 0$ , (3.13) holds.

**Case 1:** Suppose that (3.13) holds for some  $\epsilon_f > 0$ . It then follows from Lemma 3.9 that (3.14) also holds, in which case we have from (2.29a)/(2.34a), the fact that  $\mathcal{S}_f \subseteq \mathcal{F} \subseteq \mathcal{T} \setminus \mathcal{T}_0$ , part (ii) of Lemma 3.3, (3.13), (3.14), (2.57), and (3.44) that

$$\begin{aligned}
\Delta m_k^{f,t} &\geq \kappa_{ct} \epsilon_f \min \{ \epsilon_f, (1 - \kappa_B) \delta_k^t, (1 - \kappa_{fbt}) \kappa_{fbn} \} \\
&\geq \kappa_{ct} \epsilon_f \min \{ \epsilon_f, (1 - \kappa_B) \min \{ \delta_k^v, \epsilon_f, \sqrt{\kappa_v v_\infty^{\max}} \}, (1 - \kappa_{fbt}) \kappa_{fbn} \} \text{ for sufficiently large } k \in \mathcal{S}_f.
\end{aligned} \quad (3.45)$$

We now consider two subcases, deriving contradictions in each, which will prove that the condition of this case (namely, that there exists  $\epsilon_f > 0$  such that (3.13) holds) cannot occur.

**Subcase 1.1:** Suppose there exists an infinite subsequence  $\mathcal{K}_f \subseteq \mathcal{S}_f$  such that  $\{\delta_k^v\}_{k \in \mathcal{K}_f} \rightarrow 0$ . Since  $\delta_{k+1}^v < \delta_k^v$  only if  $k \in \mathcal{V} \setminus \mathcal{S}_v$  and  $\delta_{k+1}^v \leftarrow \delta_k^v$  otherwise, it follows that there exists an infinite subsequence  $\mathcal{K}_v \subseteq \mathcal{V} \setminus \mathcal{S}_v$  such that  $\{\delta_k^v\}_{k \in \mathcal{K}_v} \rightarrow 0$ . Our goal in the remainder of this subcase is to prove that for all sufficiently large  $k \in \mathcal{K}_v \subseteq \mathcal{V}$ , we have that all of the conditions of an  $f$ -iteration are satisfied, which is a contradiction since  $\mathcal{V} \cap \mathcal{F} = \emptyset$ . This will prove that such a sequence  $\mathcal{K}_f \subseteq \mathcal{S}_f$  cannot exist.

Using the fact that  $\{\delta_k^v\}_{k \in \mathcal{K}_v} \rightarrow 0$  and Lemma 3.6, we may conclude that for all sufficiently large  $k \in \mathcal{K}_v$  we have  $k \in (\mathcal{V} \cap \mathcal{D}) \setminus \mathcal{S}_v$ . In addition, since  $|\mathcal{S}_v| < \infty$  and  $\{\delta_k^v\}_{k \in \mathcal{K}_v} \rightarrow 0$ , we may conclude from part (ii) of Lemma 3.8 that  $\lim_{k \in \mathcal{K}_v} \pi_k^v = 0$ , which in turn implies with Assumption 3.1 and Lemmas 3.2 and 3.14 that  $\lim_{k \in \mathcal{K}_v} v_k = 0$ . Now, suppose that there exists an infinite subsequence  $\mathcal{K}'_v \subseteq \mathcal{K}_v$  such that  $\mathcal{K}'_v \cap \mathcal{N} = \emptyset$ . The following then hold for all sufficiently large  $k \in \mathcal{K}'_v \subseteq \mathcal{K}_v \subseteq \mathcal{V} \setminus \mathcal{S}_v$ :

- (a)  $n_k = 0$  by part (ii) of Lemma 2.6 (and thus (2.31) holds);
- (b)  $t_k \neq 0$  by (a), part (vi) of Lemma 2.6, and the fact that  $k \in \mathcal{V}$ ; and
- (c)  $v_k < \kappa_{vv} v_k^{\max} = \kappa_{vv} v_\infty^{\max}$  by Step 9, (2.8), and (3.44).

It then follows from assumption 1.1, Lemmas 3.4, the fact that  $\{\delta_k^v\}_{k \in \mathcal{K}'_v} \rightarrow 0$ , the above (c), and the bound  $\kappa_{vv} < 1$  that  $v(x_k + d_k^x, s_k + d_k^s) \leq v_k^{\max}$  for all sufficiently large  $k \in \mathcal{K}'_v$  which gives (2.36), and thus we have that all of the conditions of an  $f$ -iteration hold, so  $k \in \mathcal{F}$ . However, this is a contradiction since  $k \in \mathcal{K}'_v \subseteq \mathcal{V}$  and  $\mathcal{V} \cap \mathcal{F} = \emptyset$ . Thus, such an infinite subsequence  $\mathcal{K}'_v \subseteq \mathcal{K}_v$  cannot exist, so we may conclude that for all sufficiently large  $k \in \mathcal{K}_v$  we have  $k \in \mathcal{N}$ . To summarize, at this point in this subcase, we may assume without loss of generality that there exists an infinite subsequence  $\mathcal{K}_v \subseteq (\mathcal{N} \cap \mathcal{V} \cap \mathcal{D}) \setminus \mathcal{S}_v$  over which  $\{\delta_k^v\}_{k \in \mathcal{K}_v} \rightarrow 0$ ,  $\{\pi_k^v\}_{k \in \mathcal{K}_v} \rightarrow 0$ , and  $\{v_k\}_{k \in \mathcal{K}_v} \rightarrow 0$ .

It follows from Lemma 3.19 and the facts that  $\mathcal{K}_v \subseteq (\mathcal{N} \cap \mathcal{V} \cap \mathcal{D}) \setminus \mathcal{S}_v$  and  $\{v_k\}_{k \in \mathcal{K}_v} \rightarrow 0$  that  $m_k^v(d_k) \leq \kappa_{\text{cid}} v_k$  for all sufficiently large  $k \in \mathcal{K}_v$ . Using this fact, the triangle inequality, (3.3), Lemma 3.4, Lemma 2.9, and (3.44), we have

$$v(x_k^+, s_k^+) \leq \kappa_{\text{cid}} v_\infty^{\max} + \kappa_{v1} (\delta_k^v)^3 + \kappa_{v2} \sqrt{v_\infty^{\max}} (\delta_k^v)^2 \quad \text{for all sufficiently large } k \in \mathcal{K}_v.$$

This relationship then implies that

$$v(x_k^+, s_k^+) \leq v_\infty^{\max} = v_k^{\max} \quad \text{for all sufficiently large } k \in \mathcal{K}_v \text{ such that } (\delta_k^v)^2 \leq \min \left\{ 1, \frac{(1 - \kappa_{\text{cid}}) v_\infty^{\max}}{\kappa_{v1} + \kappa_{v2} \sqrt{v_\infty^{\max}}} \right\}.$$

Thus, since  $\{\delta_k^v\}_{k \in \mathcal{K}_v} \rightarrow 0$ , we may conclude that (2.36) holds for all sufficiently large  $k \in \mathcal{K}_v$ .

Next, suppose that for  $\epsilon_\pi > 0$  defined in (2.25a), we have

$$\|P_k^{-1} t_k\|_2 \leq \varsigma_\pi(\epsilon_\pi) \|P_k^{-1} n_k\|_2 \quad \text{for all sufficiently large } k \in \mathcal{K}_v. \quad (3.46)$$

We may then use the facts that  $\mathcal{K}_v \subseteq (\mathcal{N} \cap \mathcal{V} \cap \mathcal{D})$  and  $\{v_k\}_{k \in \mathcal{K}_v} \rightarrow 0$ , (3.46), and Lemma 3.21 to conclude that  $|\mathcal{S}_v \cap \mathcal{K}_v| = \infty$ , which contradicts the fact that  $|\mathcal{S}_v| < \infty$ . Therefore, there exists an infinite subsequence  $\mathcal{K}''_v \subseteq \mathcal{K}_v$  such that if  $k \in \mathcal{K}''_v$  then (3.46) fails.

We now show that with  $\epsilon = \epsilon_\pi$  and  $k \in \mathcal{K}''_v \subseteq \mathcal{K}_v \subseteq \mathcal{V} \setminus \mathcal{S}$ , the conditions of Lemma 3.20 hold. Consider  $k \in \mathcal{K}''_v$ . First, since  $k \in \mathcal{K}''_v \subseteq \mathcal{V}$ , we know that  $k \notin \mathcal{Y}$ . Second, since  $k \in \mathcal{K}''_v$ , we know from the previous paragraph that (3.46) does not hold, and therefore that  $t_k \neq 0$  and  $r_k$  was computed to satisfy (2.25a), (2.25b), or (2.25c). Since we have supposed that the algorithm does not terminate finitely, we may use the facts that  $\{v_k\}_{k \in \mathcal{K}_v} \rightarrow 0$  and  $\mathcal{K}''_v \subseteq \mathcal{K}_v$  along with (2.25a) to conclude that (3.37a) holds for all sufficiently large  $k \in \mathcal{K}''_v$ . Third, since  $\mathcal{K}''_v \subseteq \mathcal{K}_v$  and  $\{\delta_k^v\}_{k \in \mathcal{K}_v} \rightarrow 0$ , we have that (3.37b) holds. Fourth, we know from the definition of the set  $\mathcal{K}''_v$  that (3.46) fails, which is to say that (3.37c) holds. We may now apply Lemma 3.20 to deduce that  $t_k \neq 0$  and (2.31) holds for all sufficiently large  $k \in \mathcal{K}''_v$ . Thus, along with our previous conclusion that (2.36) holds for all sufficiently large  $k \in \mathcal{K}_v$ , we may conclude that for all sufficiently large  $k \in \mathcal{K}''_v$  we have that all of the conditions of an  $f$ -iteration are satisfied. However, as previously mentioned, this is impossible since  $\mathcal{K}''_v \subseteq \mathcal{K}_v \subseteq \mathcal{V}$  and  $\mathcal{F} \cap \mathcal{V} = \emptyset$ . Hence our stated supposition for Subcase 1.1, that there is an infinite subsequence  $\mathcal{K}_f \subseteq \mathcal{S}_f$  such that  $\{\delta_k^v\}_{k \in \mathcal{K}_f} \rightarrow 0$ , must be wrong.

**Subcase 1.2:** Suppose instead that there exists  $\epsilon_* > 0$  such that  $\delta_k^v \geq \epsilon_*$  for all  $k \in \mathcal{S}_f$ , and recall that  $|\mathcal{S}_f| = \infty$ . We may combine (3.45) and the bound  $\delta_k^v \geq \epsilon_*$  for all  $k \in \mathcal{S}_f$  to conclude that there exists  $k'$  such that

$$\Delta m_k^{f,t} \geq \kappa_{\text{ct}} \epsilon_f \min \{ \epsilon_f, (1 - \kappa_B) \min \{ \epsilon_*, \epsilon_{\mathcal{F}}, \sqrt{\kappa_v v_\infty^{\max}} \}, (1 - \kappa_{\text{ftb}}) \kappa_{\text{ftb}} \} > 0 \quad \text{for all } k' \leq k \in \mathcal{S}_f. \quad (3.47)$$

Combining the facts that  $|\mathcal{S}_v| < \infty$  and  $|\mathcal{S}_f| = \infty$ , (2.37), and (2.31) (which is required to hold for

$k \in \mathcal{F}$ ), we have that

$$f(x_{k'}, s_{k'}) - f(x_k, s_k) = \sum_{j=k', j \in \mathcal{S}}^{k-1} [f(x_j, s_j) - f(x_{j+1}, s_{j+1})] \geq \eta_1 \kappa_\delta \sum_{j=k_0, j \in \mathcal{S}}^{k-1} \Delta m_j^{f,t}, \quad (3.48)$$

which in view of (3.47) proves that  $\{f(x_k, s_k)\} \rightarrow -\infty$ . However, this is a contradiction since the barrier function is bounded below as a consequence of Lemma 3.2 and Assumptions 1.1 and 3.1.

Thus since neither Subcases 1.1 or 1.2 can happen, the premise of Case 1 cannot be true.

**Case 2:** Suppose that the condition of Case 1 does not hold, which is to say that there exists  $\mathcal{K} \subseteq \mathcal{F}$  with

$$\lim_{k \in \mathcal{K}} \pi_k^f = 0. \quad (3.49)$$

For all  $k \in \mathcal{K} \subseteq \mathcal{F} \subseteq \mathcal{T} \setminus \mathcal{T}_0$ , we have that  $t_k \neq 0$  was computed (and not reset to zero) and thus (2.25b) is false. Combining this fact with (3.49) yields

$$0 = \lim_{k \in \mathcal{K}} \pi_k^f \geq \lim_{k \in \mathcal{K}} \omega_t(\pi_k^v) \geq 0, \quad \text{which implies that} \quad \lim_{k \in \mathcal{K}} \pi_k^v = 0.$$

It follows from this fact, Assumptions 3.1 and 3.2, and Lemmas 3.2 and 3.14 that  $\{v_k\}_{k \in \mathcal{K}} \rightarrow 0$ , which when combined with (3.49) shows that (2.25a) will be satisfied for all sufficiently large  $k \in \mathcal{K}$ . However, this contradicts our supposition that the algorithm does not terminate finitely.  $\square$

The previous result proves that if the algorithm does not terminate finitely, then there are an infinite number of successful  $v$ -iterations. We now establish an important consequence of having an infinite number of successful  $v$ -iterations.

**Lemma 3.23.** *If  $|\mathcal{S}_v| = \infty$  and there exists  $\epsilon > 0$  independent of  $k$  such that (3.41) holds for all sufficiently large  $k \in \mathcal{V} \cap \mathcal{D}$ , then*

$$\delta_k^v \geq \epsilon_* \text{ for some } \epsilon_* > 0 \text{ for all } k. \quad (3.50)$$

*Proof.* First, by Lemma 3.15, the fact that  $|\mathcal{S}_v| = \infty$  implies that  $\{v_k\} \rightarrow 0$ . Hence, for sufficiently large  $k \in \mathcal{V} \cap \mathcal{D}$ , we have that (3.41) and (3.42) hold, which in turn implies by Lemma 3.21 that  $\delta_{k+1}^v \geq \delta_k^v$ . Second, if  $k \in \mathcal{V} \setminus \mathcal{D}$ , then it follows from Lemma 3.6 that  $\delta_k^v \geq \min\{\delta_k^v, \delta_k^f, \sqrt{\kappa_v v_k^{\max}}\} > \kappa_v$ . Third, if  $k \in \mathcal{V} \cup \mathcal{F}$ , then by (2.35), (2.41) and (2.44) we have that  $\delta_{k+1}^v \geq \delta_k^v$ . The result follows by combining the results of these three cases.  $\square$

We next prove a result about certain  $v$ -iterations that are unsuccessful.

**Lemma 3.24.** *If  $k \in \mathcal{V} \setminus \mathcal{S}_v$ , (3.33) holds,*

$$v_k^{\max} \leq \min \left\{ 1, \left( \frac{1 - \kappa_{\text{cld}}}{\kappa_{v1} + \kappa_{v2}} \right)^4, \left( \frac{1 - \kappa_{vv}}{\kappa_{v1} + \kappa_{v2}} \right)^4, (\kappa_v)^{\frac{12}{5}} \right\}, \quad (3.51)$$

and

$$\delta_k^v \leq (v_k^{\max})^{\frac{5}{12}}, \quad (3.52)$$

then  $k \in \mathcal{D}$  and (2.36) holds.

*Proof.* Let  $k \in \mathcal{V} \setminus \mathcal{S}_v$  and observe that (3.51) and (3.52) imply that  $\delta_k^v \leq \kappa_v$ . Hence, by Lemma 3.6, we have that  $k \in \mathcal{D}$ . That is,  $k \in (\mathcal{V} \cap \mathcal{D}) \setminus \mathcal{S}_v$ . We now consider two cases depending on whether or not  $k \in \mathcal{N}$ .

Suppose that  $k \in \mathcal{N}$  so that  $k \in (\mathcal{N} \cap \mathcal{V} \cap \mathcal{D}) \setminus \mathcal{S}_v$ . It then follows from (3.3), the triangle inequality, the requirement that (3.33) holds, and Lemmas 3.4 and 3.19 that

$$v(x_k + d_k^x, s_k + d_k^s) \leq \kappa_{\text{cld}} v_k + \kappa_{v1} (\delta_k^v)^3 + \kappa_{v2} \sqrt{v_k} (\delta_k^v)^2.$$

Then, from this inequality, Lemma 2.9, (3.52), and (3.51), we have that

$$\begin{aligned} v(x_k + d_k^x, s_k + d_k^s) &\leq \kappa_{\text{cld}} v_k^{\max} + \kappa_{v1} (v_k^{\max})^{\frac{15}{12}} + \kappa_{v2} (v_k^{\max})^{\frac{1}{2}} (v_k^{\max})^{\frac{10}{12}} \\ &= v_k^{\max} \left( \kappa_{\text{cld}} + \kappa_{v1} (v_k^{\max})^{\frac{3}{12}} + \kappa_{v2} (v_k^{\max})^{\frac{4}{12}} \right) \\ &\leq v_k^{\max} \left( \kappa_{\text{cld}} + \kappa_{v1} (v_k^{\max})^{\frac{3}{12}} + \kappa_{v2} (v_k^{\max})^{\frac{3}{12}} \right) \leq v_k^{\max}, \end{aligned}$$

which means that (2.36) holds, as desired.

Now suppose that  $k \notin \mathcal{N}$ . It then follows from (3.3), the triangle inequality, Lemmas 3.4 and 2.9, (2.29d) (which holds since  $k \in \mathcal{D}$ ), and the fact that  $v_k < \kappa_{vv} v_k^{\max}$  holds (which holds by (2.8) since  $k \notin \mathcal{N}$ ) that

$$\begin{aligned} v(x_k + d_k^x, s_k + d_k^s) &\leq m_k^v(d_k) + \kappa_{v1} (\delta_k^v)^3 + \kappa_{v2} \sqrt{v_k^{\max}} (\delta_k^v)^2 \\ &\leq v_k + \kappa_{v1} (\delta_k^v)^3 + \kappa_{v2} \sqrt{v_k^{\max}} (\delta_k^v)^2 \\ &\leq \kappa_{vv} v_k^{\max} + \kappa_{v1} (v_k^{\max})^{\frac{15}{12}} + \kappa_{v2} \sqrt{v_k^{\max}} (v_k^{\max})^{\frac{10}{12}} \\ &\leq v_k^{\max} \left( \kappa_{vv} + \kappa_{v1} (v_k^{\max})^{\frac{3}{12}} + \kappa_{v2} (v_k^{\max})^{\frac{4}{12}} \right) \\ &\leq v_k^{\max} \left( \kappa_{vv} + \kappa_{v1} (v_k^{\max})^{\frac{3}{12}} + \kappa_{v2} (v_k^{\max})^{\frac{3}{12}} \right) \leq v_k^{\max}, \end{aligned}$$

which again means that (2.36) holds, as desired.  $\square$

**Theorem 3.25.** *The set  $\mathcal{S}_v$  is finite.*

*Proof.* We prove the result by contradiction, and so suppose that  $|\mathcal{S}_v| = \infty$ . It then follows from Lemma 3.15 that  $\lim_{k \rightarrow \infty} v_k = \lim_{k \rightarrow \infty} v_k^{\max} = \lim_{k \rightarrow \infty} \pi_k^v = \lim_{k \rightarrow \infty} n_k = 0$ . Moreover, from the facts that  $\lim_{k \rightarrow \infty} v_k = 0$  and  $|\mathcal{S}_v| = \infty$ , we have that (2.25a) must not hold for all sufficiently large  $k$ , or else the algorithm would terminate finitely in Step 18 or 33, which is a contradiction. Therefore, there exists  $\epsilon_\pi > 0$  such that

$$\pi_k^f \geq \epsilon_\pi > 0 \text{ for all sufficiently large } k. \quad (3.53)$$

It follows from this fact and Lemma 3.9 that (3.14) holds. Also, with  $\epsilon = \epsilon_\pi$ , it follows from the facts that  $\lim_{k \rightarrow \infty} v_k = \lim_{k \rightarrow \infty} v_k^{\max} = 0$  and  $|\mathcal{S}_v| = \infty$  that there exists a sufficiently large  $k_0$  such that (3.33), (3.42), and (3.51) hold for all  $k \geq k_0$ .

We now prove a lower bound for  $\delta_k^v$  that holds for all sufficiently large  $k$ , written as equation (3.57) below. We prove the bound by considering two cases, the latter of which is composed of two subcases.

**Case 1:** Suppose that with  $\epsilon = \epsilon_\pi$ , (3.41) holds for all sufficiently large  $k \geq k_0$  such that  $k \in \mathcal{V} \cap \mathcal{D}$ . Then, since  $|\mathcal{S}_v| = \infty$ , we may apply Lemma 3.23 to deduce that (3.50) holds for all sufficiently large  $k \in \mathcal{V} \cap \mathcal{D}$ .

**Case 2:** Suppose that Case 1 does not hold in that there exists an infinite index set

$$\mathcal{K}_1 := \{k \geq k_0 : k \in \mathcal{V} \cap \mathcal{D} \text{ and } \|P_k^{-1} t_k\|_2 > \varsigma_{\text{tn}}(\epsilon_\pi) \|P_k^{-1} n_k\|_2\}.$$

Since  $\delta_k^v$  ( $v_k^{\max}$ ) is not decreased (increased) for  $k \in \mathcal{S}_v \cup \mathcal{Y} \cup \mathcal{F}$ , our goal is to provide a lower bound for  $\delta_k^v$  over  $k \in \mathcal{K}_1 \setminus \mathcal{S}_v$ . We do this by considering two subcases depending on whether or not  $k \in \mathcal{N}$ .

**Subcase 1:** Consider  $k$  such that  $k_0 \leq k \in \mathcal{K}_1 \setminus (\mathcal{S}_v \cup \mathcal{N})$ . Since  $k \notin \mathcal{N}$ , it follows from part (ii) of Lemma 2.6 that  $n_k = 0$ . By part (vi) of Lemma 2.6, this means that  $t_k \neq 0$  (since otherwise we would have  $k \in \mathcal{Y}$ ), which in turn means by part (v) of Lemma 2.6 that  $k \in \mathcal{T} \setminus \mathcal{T}_0$  and that (2.31) holds (since  $n_k = 0$ ). We may then conclude from the fact that  $k \in \mathcal{V} \setminus \mathcal{S}_v$ , the choice of  $k_0$  being large enough such that (3.33) and (3.51) hold for  $k \geq k_0$ , and Lemma 3.24 that if (3.52) holds, then (2.36) also holds. However, this would imply that  $k \in \mathcal{F}$ , which contradicts the definition of  $\mathcal{K}_1$  since  $\mathcal{V} \cap \mathcal{F} = \emptyset$ . Thus,

(3.52) must not hold and

$$\delta_k^v > (v_k^{\max})^{\frac{5}{12}} \text{ for all } k \text{ such that } k_0 \leq k \in \mathcal{K}_1 \setminus (\mathcal{S}_v \cup \mathcal{N}). \quad (3.54)$$

**Subcase 2:** Consider  $k$  such that  $k_0 \leq k \in (\mathcal{K}_1 \cap \mathcal{N}) \setminus \mathcal{S}_v$ . By (3.53), we have that (3.37a) holds with  $\epsilon = \epsilon_\pi$ . Similarly, by the definition of  $\mathcal{K}_1$ , we have that (3.37c) holds with  $\epsilon = \epsilon_\pi$ . Now suppose that (3.37b) with  $\epsilon = \epsilon_\pi$  and (3.52) both hold. Then, since  $k \notin \mathcal{Y}$  and (3.37a), (3.37b), and (3.37c) all hold, we may apply Lemma 3.20 to conclude that  $t_k \neq 0$  and (2.31) holds. Also, since  $k \in \mathcal{V} \setminus \mathcal{S}_v$ , we have shown that (3.33) and (3.51) hold, and we have supposed that (3.52) holds, we may apply Lemma 3.24 to conclude that (2.36) holds. Overall, we have shown that all of the conditions of an  $f$ -iteration are satisfied so that  $k \in \mathcal{F}$ . However, this contradicts the fact that  $k \in \mathcal{K}_1 \subseteq \mathcal{V}$  and  $\mathcal{V} \cap \mathcal{F} = \emptyset$ . Therefore, we may deduce that at least one of (3.37b) with  $\epsilon = \epsilon_\pi$  or (3.52) must not hold, yielding

$$\delta_k^v > \min \left\{ \varsigma_\delta(\epsilon_\pi), (v_k^{\max})^{\frac{5}{12}} \right\} \text{ for all } k \text{ such that } k_0 \leq k \in (\mathcal{K}_1 \cap \mathcal{N}) \setminus \mathcal{S}_v. \quad (3.55)$$

Combining (3.54) and (3.55) from Subcases 1 and 2 shows that, for Case 2, we have

$$\delta_k^v \geq \min \left\{ \varsigma_\delta(\epsilon_\pi), (v_k^{\max})^{\frac{5}{12}} \right\} \text{ for all } k \text{ such that } k_0 \leq k \in \mathcal{K}_1 \setminus \mathcal{S}_v. \quad (3.56)$$

Moreover, the fact that  $\lim_{k \rightarrow \infty} v_k = 0$  and Lemma 3.21 with  $\epsilon = \epsilon_\pi$  implies that for any  $k$  with  $k_0 \leq k \in (\mathcal{V} \cap \mathcal{D}) \setminus \mathcal{K}_1$ , we have  $k \in \mathcal{S}_v$ . Thus, for all  $k \geq k_0$  with  $k \in (\mathcal{V} \cap \mathcal{D}) \setminus \mathcal{S}_v$ , we have  $k \in \mathcal{K}_1 \setminus \mathcal{S}_v$ . As a result, the inequality in (3.56) holds for all  $k$  with  $k_0 \leq k \in (\mathcal{V} \cap \mathcal{D}) \setminus \mathcal{S}_v$ . This conclusion, along with the deduction that  $\delta_k^v > \kappa_{\mathcal{V}}$  for all  $k \in \mathcal{V} \setminus \mathcal{D}$  from Lemma 3.6 yields

$$\delta_k^v \geq \min \left\{ \varsigma_\delta(\epsilon_\pi), (v_k^{\max})^{\frac{5}{12}}, \kappa_{\mathcal{V}} \right\} \text{ for all } k \text{ with } k_0 \leq k \in \mathcal{V} \setminus \mathcal{S}_v,$$

which, when combined with the fact that  $\delta_k^v$  ( $v_k^{\max}$ ) is not decreased (increased) for  $k \in \mathcal{S}_v \cup \mathcal{Y} \cup \mathcal{F}$ , yields

$$\delta_k^v \geq \min \left\{ \varsigma_\delta(\epsilon_\pi), (v_k^{\max})^{\frac{5}{12}}, \kappa_{\mathcal{V}} \right\} \text{ for all } k \geq k_0.$$

Combining the results of Cases 1 and 2, we have that

$$\delta_k^v \geq \min \left\{ \epsilon_*, \varsigma_\delta(\epsilon_\pi), (v_k^{\max})^{\frac{5}{12}}, \kappa_{\mathcal{V}} \right\} \text{ for all sufficiently large } k. \quad (3.57)$$

Using this fact, (3.14), and the fact that  $\{v_k^{\max}\} \rightarrow 0$  yields

$$\min\{\delta_k^v, \delta_k^f\} \geq \min \left\{ \epsilon_*, \varsigma_\delta(\epsilon_\pi), (v_k^{\max})^{\frac{5}{12}}, \kappa_{\mathcal{V}}, \epsilon_{\mathcal{F}} \right\} = (v_k^{\max})^{\frac{5}{12}} \text{ for all sufficiently large } k. \quad (3.58)$$

Under our supposition that the set  $\mathcal{S}_v$  is infinite, at least one of the following two scenarios must occur. In both, we reach a contradiction to this supposition that  $\mathcal{S}_v$  is infinite, which proves the theorem. **Scenario 1:** Suppose that  $\mathcal{S}_1 := \mathcal{S}_v \setminus \mathcal{T}$  is infinite. For  $k \in \mathcal{S}_1$ , we have that either (2.19) does not hold or (2.25b) holds. In fact, since  $\lim_{k \rightarrow \infty} \pi_k^v = 0$  and (3.53) holds, condition (2.25b) cannot hold infinitely often for  $k \in \mathcal{S}_1$ , implying that for all sufficiently large  $k \in \mathcal{S}_1$  we have that (2.19) does not hold. Then, since  $t_k = 0$  for  $k \in \mathcal{S}_1$ , we have by part (vi) of Lemma 2.6 that  $n_k \neq 0$ . We may now use the fact that  $v_k^{\max} > 0$  for all  $k$ , (3.58), Lemmas 2.9 and 3.2, and the fact that  $\lim_{k \rightarrow \infty} v_k = 0$  to conclude that

$$\frac{\|P_k^{-1} n_k\|_2}{\min\{\delta_k^v, \delta_k^f\}} \leq \frac{\kappa_n \pi_k^v}{(v_k^{\max})^{\frac{5}{12}}} \leq \frac{\kappa_n \kappa_{\text{ub}} \|c(x_k, s_k)\|_2}{(v_k)^{\frac{5}{12}}} = \frac{\kappa_n \kappa_{\text{ub}} \|c(x_k, s_k)\|_2}{(\|c(x_k, s_k)\|_2^2)^{\frac{5}{12}}} \leq \kappa_{\text{B}} \text{ for sufficiently large } k \in \mathcal{S}_1.$$

However, this means that (2.19) holds for all sufficiently large  $k \in \mathcal{S}_1$ , contradicting our earlier conclusion that it does not. This contradiction implies that this scenario cannot occur.

**Scenario 2:** Suppose that  $\mathcal{S}_2 = \mathcal{S}_v \cap \mathcal{T}$  is infinite. Our goal is to show that for all sufficiently large

$k \in \mathcal{S}_2$ , we have that all of the conditions of an  $f$ -iteration are satisfied, which is impossible since  $\mathcal{S}_2 \subseteq \mathcal{V}$  and  $\mathcal{V} \cap \mathcal{F} = \emptyset$ . We begin by showing that (2.31) holds for all sufficiently large  $k \in \mathcal{S}_2$ . Using (3.39), the triangle and Cauchy-Schwarz inequalities, Lemma 3.2, (2.11), and the fact that  $\lim_{k \rightarrow \infty} \pi_k^v = 0$  (and hence that  $\kappa_n \pi_k \leq 1$  for all  $k$  sufficiently large), it follows as in the proof of Lemma 3.20 (see (3.40)) that

$$|\Delta m_k^{f,n}| \leq \kappa_{\text{ub}} \left( \|P_k^{-1} n_k\|_2 + \frac{1}{2} \|P_k^{-1} n_k\|_2^2 \right) \leq 2\kappa_{\text{ub}} \kappa_n \pi_k^v \leq 2\kappa_{\text{ub}}^2 \kappa_n \|c(x_k, s_k)\|_2 \quad \text{for all sufficiently large } k \in \mathcal{S}_2. \quad (3.59)$$

It also follows from the fact that  $\{v_k^{\text{max}}\} \rightarrow 0$  and Lemma 3.6 that  $k \in \mathcal{D}$  for all sufficiently large  $k \in \mathcal{S}_2$ . Moreover, since  $\mathcal{S}_2 \subseteq \mathcal{T}$ , it follows that for all  $k \in \mathcal{S}_2$  a tangential step  $t_k \neq 0$  was computed to satisfy either (2.29) or (2.34). However, for all  $k \in \mathcal{S}_2 = \mathcal{S}_v \cap \mathcal{T}$ , it follows from (2.47) that  $n_k \neq 0$  and then from part (xi) of Lemma 2.6 that  $k \in \mathcal{T}_{\mathcal{D}}$ , i.e., that (2.29) holds. This implies by (2.57) that  $\delta_k^t = \min\{\delta_k^v, \delta_k^f\}$  for sufficiently large  $k \in \mathcal{S}_2$ . It follows from this fact, the fact that  $k \in \mathcal{T}_{\mathcal{D}}$ , (2.29a), part (ii) of Lemma 3.3, (3.53), (3.58), the fact that  $\lim_{k \rightarrow \infty} v_k^{\text{max}} = 0$ , and Lemma 2.9 that

$$\begin{aligned}
 \Delta m_k^{f,t} &\geq \kappa_{\text{ct}} \epsilon_{\pi} \min \left\{ \epsilon_{\pi}, (1 - \kappa_{\text{B}}) \delta_k^t, (1 - \kappa_{\text{fbt}}) \kappa_{\text{fbn}} \right\} \\
 &= \kappa_{\text{ct}} \epsilon_{\pi} \min \left\{ \epsilon_{\pi}, (1 - \kappa_{\text{B}}) \min\{\delta_k^v, \delta_k^f\}, (1 - \kappa_{\text{fbt}}) \kappa_{\text{fbn}} \right\} \geq \kappa_{\text{ct}} \epsilon_{\pi} (1 - \kappa_{\text{B}}) (v_k^{\text{max}})^{\frac{5}{12}} \geq \kappa_{\text{ct}} \epsilon_{\pi} (1 - \kappa_{\text{B}}) (v_k)^{\frac{5}{12}} \\
 &= \kappa_{\text{ct}} \epsilon_{\pi} (1 - \kappa_{\text{B}}) \|c(x_k, s_k)\|_2^{\frac{10}{12}} \geq \frac{1}{2} \kappa_{\text{ct}} \epsilon_{\pi} (1 - \kappa_{\text{B}}) \|c(x_k, s_k)\|_2^{\frac{10}{12}} \quad \text{for all sufficiently large } k \in \mathcal{S}_2.
 \end{aligned}$$

Combining this with (3.59) and the fact that  $\lim_{k \rightarrow \infty} v_k = 0$  shows that

$$\frac{|\Delta m_k^{f,n}|}{\Delta m_k^{f,t}} \leq \frac{4\kappa_{\text{ub}}^2 \kappa_n \|c(x_k, s_k)\|_2}{\kappa_{\text{ct}} \epsilon_{\pi} (1 - \kappa_{\text{B}}) \|c(x_k, s_k)\|_2^{\frac{10}{12}}} \leq \frac{4\kappa_{\text{ub}}^2 \kappa_n \|c(x_k, s_k)\|_2^{\frac{2}{12}}}{\kappa_{\text{ct}} \epsilon_{\pi} (1 - \kappa_{\text{B}})} \leq 1 - \kappa_{\delta} \quad \text{for all sufficiently large } k \in \mathcal{S}_2.$$

Hence, (2.31) holds for sufficiently large  $k \in \mathcal{S}_2$ , as desired. From here, it follows from Step 28 that the computed tangential step is not reset to zero, i.e.,  $k \in \mathcal{T}_{\mathcal{D}} \setminus \mathcal{T}_0$  for all sufficiently large  $k \in \mathcal{S}_2$ , from which it follows that  $t_k \neq 0$  for all sufficiently large  $k \in \mathcal{S}_2$ . Moreover, since  $k \in \mathcal{S}_v$  implies by Lemma 2.9 that (2.36) holds, we have from the fact that  $\mathcal{S}_2 \subseteq \mathcal{S}_v$  that (2.36) holds for all  $k \in \mathcal{S}_2$ . To summarize, we have shown that for all sufficiently large  $k \in \mathcal{S}_2$ , we have that all conditions of an  $f$ -iteration are satisfied, which is a contradiction. Thus, this scenario cannot occur.

Overall, we have shown that under our supposition that  $|\mathcal{S}_v| = \infty$ , neither Scenario 1 nor 2 may occur. However, since one of the two must occur in order to have  $|\mathcal{S}_v| = \infty$ , we have reached contradictions to our supposition, meaning that the result is proved.  $\square$

We conclude by summarizing our convergence results.

**Theorem 3.26.** *The following hold for Algorithm 1:*

- (i) *If Assumptions 1.1, 2.1, and 3.1 hold, then either Algorithm 1 terminates finitely or there exists an infinite subsequence  $\mathcal{K}$  such that  $\lim_{k \in \mathcal{K}} \pi_k^v = 0$ . In the latter case, any limit point  $(x_*, s_*)$  of  $\{(x_k, s_k)\}_{k \in \mathcal{K}}$  satisfies  $\pi^v(x_*, s_*) = 0$  and is therefore a critical point of  $v(x, s)$  subject to  $s \geq 0$ .*
- (ii) *If Assumptions 1.1, 2.1, 3.1, and 3.2 hold, then either Algorithm 1 terminates finitely or there exists an infinite subsequence  $\mathcal{K}$  such that  $\lim_{k \in \mathcal{K}} \pi_k^v = 0$ . In the latter case, any limit point  $(x_*, s_*)$  of  $\{(x_k, s_k)\}_{k \in \mathcal{K}}$  satisfies  $v(x_*, s_*) = 0$  with  $x_*$  feasible for (NP).*
- (iii) *If Assumptions 1.1, 2.1, 3.1, 3.2, and 3.3 hold, then Algorithm 1 terminates finitely in Step 18 or 33 with an approximate first-order KKT point  $(x_k, s_k, y_k)$  for the barrier problem (1.1).*

*Proof.* Part (i) follows from Lemma 3.13, Assumption 1.1, and the criticality conditions (3.24) for minimizing  $v(x, s)$  subject to  $s \geq 0$ . Part (ii) follows from part (i) and Lemma 3.14. It remains to prove part (iii).

It follows from Theorems 3.25 and 3.22 that Algorithm 1 terminates finitely. The only way part (iii) would not hold is if Algorithm 1 terminated in Step 8 with an infeasible stationary point. However, this is not possible since if  $\pi_k = 0$ , then  $P_k J^T(x_k, s_k)c(x_k, s_k) = 0$  and thus  $c(x_k, s_k) = 0$  as a consequence of Assumption 3.3, which contradicts  $v_k > 0$ . This proves the result.  $\square$

## 4 A Trust-Funnel Algorithm for Solving the Nonlinear Optimization Problem

The previous section considers the global convergence properties of our new trust-funnel algorithm when applied to the barrier subproblem (1.1). This section describes how a sequence of barrier subproblems with decreasing values for the barrier parameter may be solved to find an approximate first-order KKT point for problem (NP) (equivalently, problem (NPs)).

To achieve our stated goal, we require the constants  $\epsilon_\pi$  and  $\epsilon_v$  in Algorithm 1 to depend on  $\mu$ . Moreover, for practical reasons, it is advisable to make other constants in Algorithm 1 depend on  $\mu$  as well. In the previous section, we did not explicitly state these dependencies, for ease of exposition, since  $\mu$  was fixed. This does not pose a problem in this section since we use Algorithm 1 to solve a sequence of barrier problems where for each particular instance the penalty parameter is fixed and therefore our previous analysis still holds. A summary of the constants that depend on  $\mu$  and precisely where they are used is given in Table 4.1. In addition to requiring them to be positive, it is practical to have them satisfy

$$\lim_{\mu \rightarrow 0} \epsilon_\pi(\mu) = \lim_{\mu \rightarrow 0} \epsilon_v(\mu) = \lim_{\mu \rightarrow 0} \kappa_{\text{fbn}}(\mu) = \lim_{\mu \rightarrow 0} \kappa_{\text{fbt}}(\mu) = 0 \quad \text{and} \quad (4.1)$$

$$\lim_{\mu \rightarrow 0} \kappa_y(\mu) = \lim_{\mu \rightarrow 0} \kappa_D(\mu) = \infty. \quad (4.2)$$

Moreover, the convergence result that we present in this section additionally assumes that

$$\epsilon_\pi(\mu_j) \leq \zeta_1 \mu_j, \quad \epsilon_v(\mu_j) \leq \zeta_2 \mu_j^2, \quad \text{and} \quad \kappa_D(\mu_j) \leq \zeta_3 \mu_j^{-\alpha} \quad (4.3)$$

for some chosen constants  $\{\zeta_1, \alpha\} \subset (0, 1)$  and  $\{\zeta_2, \zeta_3\} \subset (0, \infty)$ , and that a particular choice for the positive-definite matrix  $D_k$  defined in (2.18) is used. Specifically, for each  $1 \leq i \leq m$ , we define

$$[d_k]_i := [D_k]_{ii} := \begin{cases} \kappa_D(\mu_j) & \text{if } \mu_j [s_k]_i^{-2} > \kappa_D(\mu_j), \\ \mu_j [s_k]_i^{-2} & \text{otherwise.} \end{cases} \quad (4.4)$$

Other choices for  $D_k$ , such as the primal-dual update  $Y_k S_k^{-1}$ , are also possible, and would only require a slight modification in the proof.

With these requirements, we may now state our algorithm for solving problem (NPs).

Table 4.1: Parameters from Algorithm 1 that depend on the barrier parameter.

Parameter	Used	Parameter	Used	Parameter	Used
$\kappa_y = \kappa_y(\mu)$	(2.17)	$\kappa_D = \kappa_D(\mu)$	(2.18)	$\epsilon_\pi = \epsilon_\pi(\mu)$	(2.25a)
$\kappa_{\text{fbt}} = \kappa_{\text{fbt}}(\mu)$	(2.29b)/(2.34b)	$\kappa_{\text{fbn}} = \kappa_{\text{fbn}}(\mu)$	(2.5)/(2.11)	$\epsilon_v = \epsilon_v(\mu)$	(2.25a)

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**Algorithm 2** Trust-funnel algorithm for solving (NPs).

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- 1: **Input:**  $(x_0, s_0, y_0, \mu_0)$  satisfying  $(s_0, y_0, \mu_0) > 0$ .
  - 2: Choose a parameter  $\gamma_\mu \in (0, 1)$  and any two forcing functions  $\epsilon_\pi(\cdot)$  and  $\epsilon_v(\cdot)$ .
  - 3: Set  $(x_0^{\text{start}}, s_0^{\text{start}}, y_0^{\text{start}}) \leftarrow (x_0, s_0, y_0)$  and  $j \leftarrow 0$ .
  - 4: **loop**
  - 5: Call Algorithm 1 with input  $(x_j^{\text{start}}, s_j^{\text{start}}, y_j^{\text{start}}, \mu_j)$  and  $(\epsilon_\pi(\mu_j), \epsilon_v(\mu_j))$  to compute  $(x_{j+1}, s_{j+1}, y_{j+1})$ .
  - 6: **if** Algorithm 1 terminated in Step 8 **then**
  - 7: Return the infeasible stationary point  $(x_{j+1}, s_{j+1})$ .
  - 8: Set  $\mu_{j+1} \in (0, \gamma_\mu \mu_j]$ .
  - 9: Use  $\mu_j, \mu_{j+1}$ , and  $(x_{j+1}, s_{j+1}, y_{j+1})$  to compute the next starting point  $(x_{j+1}^{\text{start}}, s_{j+1}^{\text{start}}, y_{j+1}^{\text{start}})$ .
  - 10: Set  $j \leftarrow j + 1$ .
- 

**Theorem 4.1.** *If Assumptions 1.1, 2.1, 3.1, and 3.3 hold, and both (4.3) and (4.4) hold, then either*

- (i) *Algorithm 2 returns an infeasible stationary point in Step 7, or*
- (ii) *there exists a limit point  $(x_*, s_*, y_*)$  of the iterates  $\{(x_{j+1}, s_{j+1}, y_{j+1})\}$  computed by Algorithm 2 such that  $(x_*, s_*, y_*)$  is a first-order KKT point for problem (NPs).*

*Proof.* If statement (i) occurs, then there is nothing left to prove. Therefore, suppose that statement (i) does not occur, in which case we have that Algorithm 1 never terminates in Step 8, which by (2.25a) and (4.3) means that for all  $j \geq 0$  we have

$$\pi_{j+1}^f(y_{j+1}) \leq \epsilon_\pi(\mu_j) \leq \zeta_1 \mu_j \quad \text{and} \quad v_{j+1} \leq \epsilon_v(\mu_j) \leq \zeta_2 \mu_j^2. \quad (4.5)$$

In particular, we have that the sequence  $\{(x_{j+1}, s_{j+1}, y_{j+1})\}$  is infinite, and from the second part of (4.5), the reverse triangle inequality, Assumption 3.1, and (4.1), we have that  $\{s_{j+1}\}$  is bounded. Combining this fact with Assumption 3.1 implies the existence of an infinite index set  $\mathcal{J}$  and a point  $(x_*, s_*)$  with  $s_* \geq 0$  such that

$$\lim_{j \in \mathcal{J}} (x_{j+1}, s_{j+1}) = (x_*, s_*). \quad (4.6)$$

It follows from this fact, (4.5), and Assumption 1.1 that

$$\lim_{j \in \mathcal{J}} v_{j+1} = v(x_*, s_*) = 0. \quad (4.7)$$

We comment that for the remainder of the proof, the quantities  $P_{j+1}, n_{j+1}$ , etc. are used to represent the final values of the relevant quantities computed in Algorithm 1 when it is called in line 5 during iteration  $j$  of Algorithm 2; they are the complementary quantities to  $(x_{j+1}, s_{j+1}, y_{j+1})$ .

It follows from the definition of  $P_{j+1}$ , (2.11), (4.6), Assumption 1.1, and (4.5) that

$$\begin{aligned} \left| \frac{[n_{j+1}^s]_i}{[s_{j+1}]_i} \right| &\leq \|S_{j+1}^{-1} n_{j+1}^s\|_\infty \leq \|S_{j+1}^{-1} n_{j+1}^s\|_2 \leq \|P_{j+1}^{-1} n_{j+1}\|_2 \\ &\leq \kappa_n \pi_{j+1}^v = \mathcal{O}(\|c(x_{j+1}, s_{j+1})\|_2) = \mathcal{O}(\sqrt{v_{j+1}}) = \mathcal{O}(\mu_j). \end{aligned}$$

Since we maintain positive slack vectors throughout Algorithm 1, we may then conclude that

$$|[n_{j+1}^s]_i| = \mathcal{O}(\mu_j [s_{j+1}]_i) \quad \text{for all } 1 \leq i \leq m \text{ and } j \geq 1. \quad (4.8)$$

We now develop a crucial bound by considering two cases motivated by the definition of  $D_k$ . First, suppose that for a given  $i$  we have  $\mu_j [s_{j+1}]_i^{-2} \leq \kappa_D(\mu_j)$ , so that from (4.4) we have  $[d_{j+1}]_i = \mu_j [s_{j+1}]_i^{-2}$ . It then follows from this fact and (4.8) that

$$|[s_{j+1}]_i [d_{j+1}]_i [n_{j+1}^s]_i| = \mathcal{O}(\mu_j^2).$$

Second, suppose that for a given  $i$  we have  $\mu_j [s_{j+1}]_i^{-2} > \kappa_D(\mu_j)$ , so that from (4.4) we have  $[d_{j+1}]_i = \kappa_D(\mu_j) < \mu_j [s_{j+1}]_i^{-2}$ , and thus  $[s_{j+1}]_i^2 [d_{j+1}]_i < \mu_j$ . Combining this fact with (4.8) shows that

$$|[s_{j+1}]_i [d_{j+1}]_i [n_{j+1}^s]_i| = \mathcal{O}(\mu_j [s_{j+1}]_i^2 [d_{j+1}]_i) = \mathcal{O}(\mu_j^2). \quad (4.9)$$

Therefore, we have shown that (4.9) holds in both cases, i.e., (4.9) holds for all  $1 \leq i \leq m$  and  $j \geq 1$ . We may now use the same proof as for Lemma 3.16, combined with (4.7), (4.9), and the first part of (4.5) to deduce that  $\lim_{j \in \mathcal{J}} y_{j+1} = y_*$  for some  $y_*$  satisfying  $g(x_*) + J(x_*)^T y_* = 0$  and  $S_* y_* = 0$ . To prove that  $(x_*, s_*, y_*)$  is a first-order KKT point for problem (NPs), it only remains to prove that  $y_* \geq 0$ , which we now proceed to do.

From the first part of (4.5), we know that

$$\begin{aligned} \zeta_1 \mu_j &\geq \left\| \begin{pmatrix} g(x_{j+1}) + \nabla_{xx} \mathcal{L}(x_{j+1}, y_{j+1}^B) n_{j+1}^x + J(x_{j+1})^T y_{j+1} \\ -\mu_j e + S_{j+1} D_{j+1} n_{j+1}^s + S_{j+1} y_{j+1} \end{pmatrix} \right\|_2 \\ &\geq \left\| -\mu_j e + S_{j+1} D_{j+1} n_{j+1}^s + S_{j+1} y_{j+1} \right\|_2 \geq \left\| -\mu_j e + S_{j+1} D_{j+1} n_{j+1}^s + S_{j+1} y_{j+1} \right\|_\infty \\ &\geq |-\mu_j + [s_{j+1}]_i [d_{j+1}]_i [n_{j+1}^s]_i + [s_{j+1}]_i [y_{j+1}]_i| \quad \text{for all } 1 \leq i \leq m. \end{aligned} \quad (4.10)$$

We now consider two cases. First, suppose that  $i$  is such that  $[s_*]_i > 0$ . In this case it follows from (4.10), (4.9), the fact that  $\mu_j \rightarrow 0$ , and (4.6) that  $\lim_{j \in \mathcal{J}} [y_{j+1}]_i = [y_*]_i = 0$ , as desired. Second, suppose that  $i$  is such that  $[s_*]_i = 0$ . It may be observed from (4.10) that

$$-\zeta_1 \mu_j \leq -\mu_j + [s_{j+1}]_i [d_{j+1}]_i [n_{j+1}^s]_i + [s_{j+1}]_i [y_{j+1}]_i,$$

and hence that

$$[y_{j+1}]_i \geq \frac{-\zeta_1 \mu_j + \mu_j - [s_{j+1}]_i [d_{j+1}]_i [n_{j+1}^s]_i}{[s_{j+1}]_i}.$$

It follows from the previous inequality, the facts that  $\zeta_1 \in (0, 1)$  and  $\mu_j \rightarrow 0$ , (4.9), and the fact that the slack vectors are maintained to be positive in Algorithm 1, that  $[y_{j+1}]_i > 0$  for all sufficiently large  $j$ . Combining this with  $\lim_{j \in \mathcal{J}} y_{j+1} = y_*$  shows that  $[y_*]_i \geq 0$ . This completes the proof.  $\square$

## 5 Conclusion and discussion

In this paper, we have presented a new algorithm for solving constrained nonlinear optimization problems. The algorithm is of the inexact barrier-SQP variety, i.e., it approximately solves a sequence of barrier subproblems using an inexact SQP method. In Sections 2 and 3, we proved that each barrier subproblem could be solved approximately using a new inexact-SQP method based on a trust-funnel mechanism (not requiring a filter or penalty function). The algorithm is extremely flexible in that, during each iteration, it automatically determines the types of steps and updates that are expected to be most productive, where potential productivity is determined by available criticality measures. In each iteration, each subproblem may be solved approximately using matrix-free iterative methods, which means that the algorithm is viable for solving large-scale barrier subproblems. We then proved in Section 4 that an approximate solution of the original nonlinear optimization problem may be obtained by approximately solving a sequence of barrier subproblems for a decreasing sequence of barrier parameters.

Although we have not considered them explicitly in this paper, we remark that equality constraints, call them  $c_E(x) = 0$ , may easily be included in our algorithm and analysis. To do this, one may simply redefine

$$c(x, s) := \begin{pmatrix} c(x) + s \\ c_E(x) \end{pmatrix}$$

and adjust the barrier problem (1.1), violation measure (2.1) and  $v$ -criticality measure (2.7) in obvious

ways. Clearly, two-sided bounds on inequality constraints may also be incorporated in a similar fashion.

We are currently implementing our new algorithm. Once complete, it will be part of the GALAHAD [21] thread-safe library of Fortran 90 packages for the numerical solution of optimization problems.

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