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A geometric stabilization of planar switched systems

Cyrille Chenavier * Rosane Ushirobira * Giorgio Valmorbida **

* Inria, Univ. Lille, CNRS, UMR 9189 - CRISAL, F-59000 Lille, France. (e-mail: cyrille.chenavier@inria.fr, rosane.ushirobira@inria.fr).
** L2S, Université Paris XI, CNRS 91192, GIF-sur-Yvette, France. (e-mail: giorgio.valmorbida@l2s.centralesupelec.fr).

Abstract: In this paper, we investigate a particular class of switching functions between two linear systems in the plan. The considered functions are defined in terms of geometric constructions. More precisely, we introduce two criteria for proving uniform stability of such functions, both criteria are based on the construction of a Lyapunov function. The first criterion is constructed in terms of an algebraic reformulation of the problem and linear matrix inequalities. The second one is purely geometric. Finally, we illustrate the second method with a numerical example.

Keywords: Linear systems, switching functions, stabilization, algebraic approaches, geometric approaches.

1. INTRODUCTION

A switched system is a (continuous or discrete-time) dynamical system composed of a finite number of subsystems together with a rule, called the switching function or the switching law, that orchestrates the switching between subsystems. Such systems have been studied in various areas of control theory. In particular, stability DeCarlo et al. (2000); Liberzon and Morse (1999); Molchanov and Pyatnitskiy (1989), controllability Sun (2006); Sun et al. (2002), observability Bemporad et al. (2000); Egerstedt and Babaali (2005); Hespanha et al. (2005), stabilization Johansson (2003); Pettersson (2003); Sun and Ge (2005), optimal control Bemporad and Morari (1999); X. and Antsaklis (2004), aperiodic sampling Hetel et al. (2017), or for discrete-time delay systems Hetel et al. (2017); Fridman (2014), for instance.

Stability and stabilization problems generally consist in searching for or proving that a class of switching functions induce, for every initial condition, a convergent trajectory, see Lin and Antsaklis (2005); Sun and Ge (2005). Numerical methods for proving stability results are based on linear matrix inequalities (LMI) and Lyapunov functions or their adaptations, such as, quasi-quadratic Hu and Blanchini (2010), parameter dependent Daafouz et al. (2002), path-dependent Lee and Dullerud (2006), non-monotonic Athanasopoulos and Lazar (2014); Megretski (1997); Bliman and Ferrari-Trecate (2003); Kruszewski et al. (2008); Ahmadi and Parrilo (2008), with an augmented state vector Gomide and Lacerda (2018), composite quadratic Hu and Blanchini (2010); Hetel et al. (2011) Lyapunov functions or using a Gaussian elimination procedure Aleksandrov et al. (2011).

In this work, we are interested in linear planar switched systems with two subsystems. A complete stability analysis of such systems was done using algebraic invariants, namely the traces and the determinants of the two matrices of the two subsystems Balde et al. (2009). In the present paper, we are interested in stabilization problems, where we wish to construct a stable switching function using geometric methods. Indeed, our original goal is to partition the plane into four regions using two distinct lines passing through the origin, and define the switching signal as being the same on two adjacent regions, but alternating while passing from a region to another, see Fig. 1. A different problem is studied here: we assume that two lines passing through the origin are given, and we search for criteria to guarantee that the switching signal defined by these two lines is globally stabilizing, that is, the trajectories induced by this signal converge to the origin. Two such criteria are proposed, both of them involve the design of Lyapunov functions. The first one is based on an algebraic reformulation of the problem in terms of quadratic forms, and the Lyapunov function is constructed in terms of solutions of linear matrix inequalities. The second approach uses purely geometric tools, and the Lyapunov function is constructed in terms of the existence of a parallelogram such that the trajectories are contracted along them. As an illustration of this method we recover an example treated in Lin and Antsaklis (2007).

The paper is organized as follows. In Section 2, we recall general notions on continuous-time switched systems, and classical Lyapunov functions properties to prove global exponential stability of such systems. In Section 3, we formulate our general problem and give two reformulations that are used in the sequel. In Section 4, our two main results are proven: two sufficient conditions, one algebraic and the other geometric, for the existence of a solution to the general problem. In Section 5, we illustrate the geometric condition with a complete numerical example.

2. PRELIMINARIES

Let us begin with some notation. For $n, m$ two strictly positive integers, the set of real $n \times m$-matrices is denoted by $\mathbb{R}^{n \times m}$. Let $\| \cdot \|$ denote the Euclidean norm on $\mathbb{R}^n$. For a matrix $P \in \mathbb{R}^{n \times n}$, we write $P > 0$ if $P$ is a positive definite matrix and $P < 0$ if $P$ is a negative definite matrix.
In this short section, we recall some general notions of continuous-time switched linear systems that are used in the sequel.

Consider $n$, $p$, two strictly positive integers, and a finite set of matrices $\mathbf{A} = \{ \mathbf{A}_i \in \mathbb{R}^{n \times n} \mid 1 \leq i \leq n \}$. A continuous-time switched linear system is described by:

$$\dot{x}(t) = \mathbf{A}_{\sigma(t)} x(t), \quad t \in \mathbb{R}_{>0}, \quad x(0) = x_0 \in \mathbb{R}^n \tag{1}$$

where $x : \mathbb{R}_{>0} \rightarrow \mathbb{R}^n$ represents the system state, $x_0$ is the initial condition and $\sigma : \mathbb{R}_{>0} \rightarrow \{1, \cdots, p\}$ is a switching function. The flow associated to $\sigma$ is denoted by $(t, x_0) \rightarrow \phi_\sigma(t, x_0)$.

Definition 1. Given a switching function $\sigma$, the equilibrium point $x = 0$ of the switched linear system (1) is said to be globally exponentially stable if there exist constant $c > 0$ and $\lambda > 0$ such that

$$\| \phi_\sigma(t, x_0) \|^2 \leq c e^{-\lambda t} \| x_0 \|^2 \tag{2}$$

holds for all initial conditions $x_0 \in \mathbb{R}^n$ and all $t \in \mathbb{R}_{>0}$. In this situation, we also say that the system (1) is globally exponentially stable.

In the sequel, we will work with systems of the form (1) with $n = p = 2$: so $\mathbf{A} = \{ \mathbf{A}_1, \mathbf{A}_2 \in \mathbb{R}^{2 \times 2} \}$ and

$$\dot{x}(t) = \mathbf{A}_{\sigma(t)} x(t), \quad t \in \mathbb{R}_{>0}, \quad x(0) = x_0 \in \mathbb{R}^2 \tag{3}$$

with $\sigma : \mathbb{R}_{>0} \rightarrow \{1, 2\}$.

Our goal is to provide algebraic and geometric conditions on the switching function $\sigma$ to prove that (3) is globally exponentially stable. Our proofs are based on the design of Lyapunov functions (so, positive functions $V : \mathbb{R}^2 \rightarrow \mathbb{R}_{>0}$, with the property that $V$ is decreasing along trajectories of (3)). Indeed, recall that the existence of such a function guarantees global exponential stability.

3. GENERAL PROBLEM

For two angles $\theta_1, \theta_2 \in [0, 2\pi)$ such that $\theta_1 \neq \theta_2 \mod (\pi)$, denote by $\mathcal{D}_{\theta_i}$ the unique line passing through the origin making an angle $\theta_i \mod (\pi)$ with the $x_1$-axis.

Our general problem can be stated as following: given two square matrices $\mathbf{A}_1, \mathbf{A}_2 \in \mathbb{R}^{2 \times 2}$, do there exist angles $\theta_1$ and $\theta_2$ as above such that (3) is globally exponentially stable, with the switching function $\sigma : \mathbb{R}_{>0} \rightarrow \{1, 2\}$ defined by $\sigma(t) = i$ if $x(t) \in \Sigma_i$, where $\Sigma_1$, $\Sigma_2$ are the two regions determined respectively by $\mathcal{D}_{\theta_1}$ and $\mathcal{D}_{\theta_2}$, and pictured in Fig. 1. We denote by $\Sigma_i$ ($i = 1, 2$) the topological closures. Remark that the lines $\mathcal{D}_{\theta_i}$ form the intersection of the two regions $\Sigma_i$, $i = 1, 2$.

Next, we will use the following terminology:

Definition 2. We say that a pair of angles $(\theta_1, \theta_2)$ is stabilizing for $(\mathbf{A}_1, \mathbf{A}_2)$ if it is a solution to the general problem.

In the next section, two sufficient conditions are presented such that a given pair of angles $(\theta_1, \theta_2)$ is stabilizing for $(\mathbf{A}_1, \mathbf{A}_2)$. The first sufficient condition, given in Section 4.1, is algebraic, and the second one, given in Section 4.2, is geometric. In these sections, we use reformulations of the problem by giving other descriptions of Fig. 1.

3.1 Algebraic formulation

The algebraic reformulation of Section 4.1 is based on the following proposition.

Proposition 3. There exists a one-to-one correspondence between pairs of angles $(\theta_1, \theta_2)$ such that $\theta_1 \neq \theta_2 \mod (\pi)$ and real symmetric matrices $\mathbf{R}$ with eigenvalues $(\lambda, -1)$, where $\lambda > 0$.

Proof. It is easy to see that pairs of angles that are different modulo $\pi$ are in bijective correspondence with pairs of distinct lines passing through the origin. Given such a pair of distinct lines, there exists a basis composed of orthonormal unit vectors and a scalar $a \neq 0$ such that the two lines are represented by the two equations

$$\tilde{x}_2 = a \tilde{x}_1, \quad \tilde{x}_2 = -a \tilde{x}_1. \tag{4}$$

In this coordinate system, these lines are solutions of the equation $\tilde{x}^T \tilde{R} \tilde{x} = 0$, where

$$\tilde{R} = \begin{pmatrix} a^2 & 0 \\ 0 & -1 \end{pmatrix}. \tag{5}$$

The matrix $\tilde{R}$ has eigenvalues $-1$ and $a^2 > 0$. In the original coordinate system, the two lines are solutions of $x^T \mathbf{R} x = 0$, where $\mathbf{R} = (R_{\theta})^T R_{\theta}$, with $R_{\theta}$ the rotation matrix of angle $\theta$ corresponding to the change of coordinates. So $\mathbf{R}$ has the same eigenvalues that $\tilde{R}$, which proves one implication. Conversely, let $\mathbf{R}$ be a real symmetric matrix with eigenvalues $\lambda > 0$ and $-1$, so that $\mathbf{R}$ admits a diagonal form $\tilde{R}$ such as (5). In the coordinate system corresponding to this diagonal form, the two lines with equations such as in (4) are distinct, which proves the other direction.

Using the previous notation, from Proposition 3, we deduce

$$\mathcal{D}_{\theta_1} \cup \mathcal{D}_{\theta_2} = \{ x \in \mathbb{R}^2 \mid x^T \mathbf{R} x = 0 \}.$$
1. That is, they are not pointing in the same direction.

and a strictly negative eigenvalue. Moreover, a real symmetric matrix with a strictly positive and a strictly negative eigenvalue is nothing but a real symmetric matrix with a strictly negative determinant. Hence, by the Proposition 3 an algebraic characterization of Fig.1 can be proposed. Given a real symmetric matrix \( R \) with a strictly negative determinant, let \( v_1 \) and \( v_2 \) be two independent vectors \(^1\) that are solutions to the quadratic equation \( x^T Rx = 0 \). The vector \( v_1 \) is a direction vector of \( D_{θ_i} \) \((i = 1, 2)\), so if we allow to change \( R \) by \(-R\), we may assume that \( O_1 \) is the region where the quadratic form \( x^T Rx \) is strictly positive, and \( O_2 \) is the region where it is negative. Hence, Fig. 1 corresponds to the diagram given in Fig. 2.

### 3.2 Geometric formulation

The geometric reformulation of Fig. 1 consists in starting with the lines \( D_{θ_1} \) and \( D_{θ_2} \) instead of the angles, that is, we consider two different lines \( D_1 \) and \( D_2 \) passing through the origin, and we denote by \( O_1 \) and \( O_2 \) the induced regions. This is pictured in Fig. 3.

To finish this section, it remains to adapt Definition 2 to our new situations.

**Definition 4.** (1) We say that a real symmetric matrix with strictly negative determinant is stabilizing for \((A_1,A_2)\) if the corresponding pair of angles by Proposition 3 is stabilizing for \((A_1,A_2)\).

(2) We say that a pair of lines \((D_1,D_2)\) is stabilizing for \((A_1,A_2)\) if the pair of angles they define with the \(x_1\)-axis is stabilizing for \((A_1,A_2)\).

### 4. MAIN RESULTS

#### 4.1 A sufficient algebraic condition

In this subsection, we fix a symmetric matrix \( R \) with strictly negative determinant as well as two independent vectors \( v_1 \) and \( v_2 \), solutions to \( x^T Rx = 0 \). Let \( O_1 \) and \( O_2 \) be the regions they define, respectively, and let \( \overline{O}_1, \overline{O}_2 \) be their topological closures.

#### 4.2 A sufficient geometric condition

In this subsection, we fix two different lines \( D_1 \) and \( D_2 \) passing through the origin. Let \( O_1 \) and \( O_2 \) be the regions they define

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\(^1\) With the previous notations, from Proposition 3, this intersection is \( D_{θ_1} \cup D_{θ_2} \).
Consider the system (3). Let \( p \in \bar{D} \). If there exist a contractive pair \((A_1, A_2)\) such that there exist systems with a stabilizing switch induced by a Lyapunov function. The required notions are defined below.

**Definition 6.** Let \( \bar{D} \) be a line passing through the origin and let \( p, d \in \bar{D} \). Let \( d \) be an orthogonal vector at \( \bar{D} \) in \( p \). We say that no sliding motion occurs at \( p \) if
\[
(d^T A_1 d)(d^T A_2 d) > 0.
\]

If no sliding motion occurs at any point of \( \bar{D} \), we say that \( \bar{D} \) induces no sliding motion for \((A_1, A_2)\).

The previous definition means that both matrices \( A_1 \) and \( A_2 \) point in the same direction at every point of \( \bar{D} \), that is, the trajectory defined by the matrices necessarily cross \( \bar{D} \). Equivalently, that means that no trajectory stays on \( \bar{D} \).  

**Definition 7.** Let \( L_1, L_2 \in \mathbb{R}^{1 \times 2} \). Given two lines \( D_1 \) and \( D_2 \), if there exist \( \lambda_1, \lambda_2 > 0 \) such that

(i) \( D_1 \) and \( D_2 \) are the diagonals of the parallelogram bounded by the equations \( |L_i x| = \lambda_i, i = 1, 2 \),

(ii) \( D_1 \) and \( D_2 \) are the diagonals of the parallelogram bounded by the equations \( |L_i x| = \lambda_i, i = 1, 2 \),

\( \lambda_i \) is the auxiliary system that is asymptotically stable.

\[
L_i A_i R_i \xi(t) = L_i A_i R_i \xi(t).
\]

**Proof.** The auxiliary system (7) is one-dimensional, so that it is asymptotically stable if and only if \( L_i A_i R_i < 0 \). Moreover, if \( x \) such that \( L_i x = \lambda_i \), with \( \lambda_i > 0 \), as in Definition 7, then \( x = \lambda_i R_i \). Thus, \( L_i A_i R_i < 0 \) is equivalent to \( L_i A_i x < 0 \), which shows the proposition.

Now, we may introduce the main result of the section.

**Theorem 9.** Consider the system (3). Let \( D_1, D_2 \) be two lines passing through the origin inducing no sliding motion for \((A_1, A_2)\). If there exists a contractive pair \((L_1, L_2)\) for \((D_1, D_2)\), then \((D_1, D_2)\) is stabilizing for \((A_1, A_2)\).

**Proof.** Consider the notations of Definition 7. Set \( \Omega \) to be the region defined by points \( p \in \mathbb{R}^2 \) such that the line passing through \( p \) and the origin meets one of the lines \( L_i p = \pm \lambda_i \). Let \( x \) be the trajectory defined by \( x(0) = x_0 \in \mathbb{R}^2 \) and a switching law \( \delta(t) = i \) if \( x(t) \in \Omega_i, \forall t \in \mathbb{R} \). Since \( D_1 \) and \( D_2 \) are the diagonals of the parallelogram defined such as in Definition 7, the region \( \Omega \) is equal to \( D_i \), and \( \delta \) is equal to \( \sigma \). Hence, it is sufficient to show that the trajectory \( x \) converges exponentially to 0.

Consider the positive definite function \( V : \mathbb{R}^2 \to \mathbb{R} \) defined by \( V(p) = |L_i p| \) if \( p \in \Omega_i \). Remark that \( V \) is well defined since the regions \( \Omega_1 \) and \( \Omega_2 \) determine a partition of \( \mathbb{R}^2 \). We show that the Dini derivative \( D^+ V \) of \( V \) is strictly negative along \( x \). At time \( t_0 \), \( x(t_0) \) belongs to \( \Omega \). First, assume that no switching occurs at \( t_0 \), that is, \( x(t_0) \) belongs to the interior of \( \Omega_i \). Recall from Blanchini (1995) that the Dini derivative along \( x \) at \( t_0 \) satisfies
\[
D^+ V(x(t_0)) = \lim_{t \to t_0, t > 0} \frac{V(x(t_0) + t \xi(x(t_0))) - V(x(t_0))}{t}.
\]

If \( L_i x(t_0) > 0 \), then we have \( L_i x(t_0) < 0 \) in this case, we have \( V(x(t_0) + t \xi(x(t_0))) - V(x(t_0)) \) is strictly smaller than \( L_i x(t_0) = V(x(t_0)) \), so that
\[
D^+ V(x(t_0)) < 0.
\]

If \( L_i x(t_0) < 0 \), then, by adapting the previous arguments, we show \( D^+ V(x(t_0)) < 0 \).

Now, if a switching occurs at time \( t_0 \), then \( x(t_0) \) belongs to \( D_i \cup D_j \), since no sliding motion occurs on these lines, \( x(t) \) belongs to \( \Omega_j \), \( j \neq i \), for \( t > t_0 \) sufficiently small. By replacing \( i \) by \( j \) in (8) and by adapting the reasoning of the previous paragraph, we show that \( D^+ V(x(t_0)) < 0 \).

Let us finish this section by showing that the existence of a contracting pair for \((D_1, D_2)\) is not necessary for the latter to be stabilizing. The proof of Theorem 9 is based on the construction of a piecewise Lyapunov function \( V \). In Theorem 10, we show that there exist systems with a stabilizing switch induced by a stabilizing pair of matrices but without any Lyapunov function such as \( V \).

Before that, we recall from Balde et al. (2009) the notion of worst trajectory for \((A_1, A_2) \in \mathbb{R}^{2 \times 2})\); this is the trajectory \( x \) such that at each \( t, \dot{x}(t) \) forms the smallest angle in clockwise sense with the exiting radial direction. In other words, it is the trajectory which moves away in the fastest from the origin. On the other hand, the best trajectory is the worst trajectory for \((-A_1, -A_2)\); this is the trajectory which goes the fastest to the origin. From Balde et al. (2009), the switching signal corresponding to this trajectory is orchestrated by a pair of lines passing through the origin.

**Theorem 10.** There exist matrices \( A_1, A_2 \in \mathbb{R}^{2 \times 2} \) and a stabilizing pair \((D_1, D_2)\) for \((A_1, A_2)\) such that no contracting pair exists for \((D_1, D_2)\).

**Proof.** Consider two anti-Hurwitz matrices, that is, the real parts of their eigenvalues are non-negative, and such that the best trajectory \( x \) is periodic. Let \((D_1, D_2)\) be the lines inducing the switching signal corresponding to \( x \). Now, consider a pair of matrices such that their best trajectory goes to zero and is close to \( x \). By continuity, this trajectory is orchestrated by a feedback defined by a pair of lines \((D_1', D_2')\) closed to \((D_1, D_2)\). If the condition of Theorem 9 is necessary, then there exists \( V^x \) such as in the proof. When \( e \) goes to zero, \( V^x \) goes to a nonzero function \( V \). Moreover, the derivative of \( V \) along \( x \) vanishes since the latter is periodic, that is we have \( \dot{x}(t)V(x(t)) = 0 \).
That implies that \( \dot{x}(t) = 0 \), that is \( x \) is constant, which is a contradiction.

5. EXAMPLE

In this section, we illustrate Theorem 9 with a numerical example coming from Lin and Antsaklis (2007). Consider the two matrices

\[
A_1 := \begin{pmatrix} 0 & 10 \\ 0 & 0 \end{pmatrix}, \quad A_2 := \begin{pmatrix} 1.5 & 2 \\ -2 & -0.5 \end{pmatrix}.
\]

Our objective is to construct a stabilizing pair of lines for \((A_1, A_2)\). We proceed in several steps. In particular, we are looking for two matrices \(L_i := (a_i b_i), \ i = 1, 2\), which are contractible for the pair of lines we wish to construct. We have

\[
L_1A_1 = (0 \ 10a_1), \quad L_2A_2 = (1.5a_2 - 2b_2 \ 2a_2 - 0.5b_2).
\]

We will use \(\Omega_1\) and \(\Omega_2\) as parameters. They are submitted to the restrictions that they form a partition of \(\mathbb{R}^2\) and that \(L_0A_i\) is strictly negative on one of the half-regions of \(\Omega_i\).

5.1 Step 1

Letting \( x := (1, 0)^\top \), we have \( L_1A_1x = 0 \). Hence, \( x \) belongs to \(\Omega_2\), so that we must have \( L_2A_2x < 0 \). That imposes the following restriction:

\[
\frac{3a_2}{4} < b_2. \tag{9}
\]

Moreover, \(\Omega_i\) being cones, there exists \( x' := (x_1, x_2)^\top \in \Omega_1 \) such that \( x_2 > 0 \). The inequality \( L_1A_1x' = 10a_1x_2 < 0 \) gives the following restriction:

\[
a_1 < 0. \tag{10}
\]

5.2 Step 2

We formalize \(L_1\) and \(L_2\) by taking into account (9) and (10), that is we search for these matrices as follows:

\[
L_1 = (-1 \ b_1), \quad L_2 = (1 \ b_2),
\]

with \( b_2 > \frac{3}{4} \).

5.3 Step 3

We search the top right corner of the parallelogram as in Definition 7 at a point \( p_1 \) with coordinates \((1, y_0)\). For that, we select \( y_0 \) such that \( L_2A_2y_0 = 0 \), that is

\[
y_0 = \frac{2b_2 - 1.5}{2 - 0.5b_2}.
\]

We freely select \( b_2 = 1 \), so that \( y_0 = \frac{1}{4} \), and

\[
p_1 = \left( 1, \frac{1}{3} \right). \tag{11}
\]

In particular, for every \( y' < y_0 \), the point \((1, y')\) is in the region \( L_2A_2 < 0 \). Moreover, we already have

\[
L_2 = (1 \ 1). \tag{12}
\]

5.4 Step 4

We search the bottom right corner \( p_2 \) of the parallelogram. Applying the criterion of Theorem 9, the segments \([p_1, p_2]\) and \([p_1, -p_2]\) have to be in the regions \( L_2A_2 < 0 \) and \( L_1A_1 < 0 \), respectively. From the previous step, for the first condition, we may select \( p_2 \) in the right half-plan with the second coordinate strictly smaller than \( \frac{1}{4} \). For the second condition, \(-p_2\) must be in the upper half-plan. Finally, \( p_2 \) must belong to the line directed by \(L_2\) and passing through \( p_1 \), hence we select

\[
p_2 = \left( 19 \frac{1}{12}, -\frac{1}{4} \right). \tag{13}
\]

Now, we obtain \( b_1 \) since the line passing through \(-p_2\) and \( p_1 \) is directed by \( L_1\):

\[
L_1 = (1 - 31). \tag{14}
\]

5.5 Step 5

We obtain the two lines \(D_1\) and \(D_2\) that are the diagonals passing through \( p_1 \) and \(-p_1\) and by \( p_2 \) and \(-p_2\), respectively: \(D_1\) and \(D_2\) have equations \( x_2 = \frac{1}{3}x_1 \) and \( x_2 = -\frac{1}{3}x_1 \), respectively. Finally, the switching function defined by these two lines induces a globally exponentially stable system (3) since, by construction, \((L_1, L_2)\) is contractive for \((D_1, D_2)\), so \((D_1, D_2)\) is stabilizing for \((A_1, A_2)\).

6. CONCLUSION

We presented two approaches for proving stability of a continuous-time switched system defined by a pair of 2-dimensional square matrices. These proofs were based on the design of Lyapunov functions: by using LMIs and algebraic tools for the first one and by using a geometric method for the second. This work could be extended into the following two directions. The first one will consist in achieving algorithmic constructions from our results. The second one will be to provide a full characterization of the pair of matrices having a solution to the general problem we introduced at the beginning of Section 3.

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