From max-plus algebra to nonexpansive mappings: a nonlinear theory for discrete event systems

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Abstract

Discrete event systems provide a useful abstraction for modelling a wide variety of systems: digital circuits, communication networks, manufacturing plants, etc. Their dynamics—stability, equilibrium states, cyclical behaviour, asymptotic average delays—are of vital importance to system designers. However, in marked contrast to continuous dynamical systems, there has been little systematic mathematical theory that designers can draw upon. In this paper we survey the development of such a theory, based on the dynamics of maps which are nonexpansive in the ℓ^∞ norm. This has its origins in linear algebra over the max-plus semiring but extends to a nonlinear theory that encompasses a variety of problems arising in other mathematical disciplines. We concentrate on the mathematical aspects and set out several open problems.

Keywords: cycle time, discrete event system, fixed point, max-plus semiring, nonexpansive map, nonlinear eigenvalue, nonnegative matrix, topical function.

1 Introduction

In this paper we shall study functions $F : \mathbb{R}^n \to \mathbb{R}^n$ which are homogeneous

- $\forall x \in \mathbb{R}^n, \ \ \forall h \in \mathbb{R}, \quad F(x_1 + h, \cdots, x_n + h) = (F_1(x) + h, \cdots, F_n(x) + h)$ H

and monotonic with respect to the usual product ordering on $\mathbb{R}^n$

- $\forall x, y \in \mathbb{R}^n, \quad x \leq y \ \Rightarrow \ F(x) \leq F(y)\,.$ M

As we shall see, such functions must necessarily be nonexpansive in the ℓ^∞ norm

- $\forall x, y \in \mathbb{R}^n, \quad \|F(x) - F(y)\| \leq \|x - y\|$ N

where $\|x\| = \max_{1 \leq i \leq n} |x_i|$. Functions of this kind have arisen recently in several contexts, [3, 34, 40, 46, 58], and we follow Gunawardena and Keane in calling them topical functions. We shall be concerned with their dynamics: with the behaviour of the functions under iteration and with such related questions as the existence of fixed points and the behaviour of trajectories $F^k(x)$ as $k \to \infty$.

Topical functions encompass maps and operators arising in a remarkable variety of mathematical disciplines: matrices over the max-plus semiring, nonnegative matrices of classical Perron-Frobenius theory (after suitable transformation), Leontieff substitution systems of mathematical economics, dynamic programming operators of games and of Markov decision processes, nonlinear operators arising in matrix scaling problems and demographic modelling, renormalisation operators associated to diffusions on fractals, etc (see §2).

The motivation for developing a theory of topical functions comes, in part, from the problem of modelling discrete event systems. These are best defined informally as systems comprising a finite set of events each of which can occur repeatedly. This is a convenient abstraction by which to study a variety of systems arising in real life: digital circuits, in which the events might be the voltage transitions on the wires in the circuit; communication networks, in which the events might be the arrival of packets at nodes in the network; manufacturing systems, in which the events might be the completion of a job at a machine. In designing such systems, engineers have to grapple with dynamical questions: the existence of equilibria or cyclical behaviour, whether or not the system is stable, how fast or slow the system is operating and what it might do "in the long term". However, in marked contrast to continuous dynamical systems, there has been little systematic mathematical theory that designers can draw upon.

To see why topical functions might be relevant to answering such questions, consider the following scenario. Choose some ordering of the events in the discrete event system, so that each event is associated to one of the numbers $\{1, \cdots, n\}$. Let x_i denote the time of occurrence of event i, relative to some arbitrarily chosen origin of time. Suppose that the time evolution of the system is such that, for some function $F : \mathbb{R}^n \to \mathbb{R}^n$, the time of next occurrence of event i is given by $F_i(x)$. In this case, the evolution of the system is captured by the dynamics of the function F, which conceals within itself the details of the system.

Given this scenario, what properties should be expected of F? First, since the origin of time is irrelevant, the times of occurrences of all events can all be changed by the same amount. This is exactly the property of homogeneity. Second, it is not unreasonable to ask that, if the times of occurrences of some events are delayed then this cannot cause any event to occur more quickly. This corresponds exactly to monotonicity with respect to the product ordering on $\mathbb{R}^n$. In this scenario, topical functions arise very naturally.

There are discrete event systems of practical importance which can be modelled even in this restricted manner. In particular, matrices over the max-plus semiring have provided a linear algebraic foundation for an important class of discrete event systems (see §2.1.1). Topical functions may be seen as a nonlinear generalisation of this. However, there are obvious limitations to the scenario above. It does not allow for nondeterminism—from any given state $x \in \mathbb{R}^n$, the system evolves to one and only one state, $F(x)$—nor for stochastic uncertainty in the system description. The theory of a single topical function can be broadened to accommodate both of these. Nondeterminism can be modelled in terms of the semigroup generated by a set of topical functions: $\{F_a \mid a \in A\}$. The state of the system can then change to any of the states $F_a(x)$. This is exactly the way in which nondeterminism is modelled in automata theory. Stochastic behaviour can be modelled by using random topical functions: the single topical function F is replaced by a random variable from some suitable measure space into the space of topical functions.

Both of these directions lie outside the scope of the present paper and are discussed further in [33]. This paper concerns itself with the theory of a single topical function. This provides the foundation for all broader applications and already presents challenging unsolved problems.

A more serious difficulty with the scenario above is the assumption of monotonicity. This is not as compelling as that of homogeneity: it is easy to construct systems in which monotonicity is not satisfied. Nevertheless it is a convenient assumption which holds for many systems of practical interest. Glasserman and Yao have used a form of monotonicity as the foundation for their treatment of discrete event systems in [26]. In our context, it is crucially related to the property of nonexpansiveness, as shown by the following result of Crandall and Tartar.

Proposition 1.1 ([16, Proposition 2]) *If $F : \mathbb{R}^n \rightarrow \mathbb{R}^n$ satisfies* H *then it satisfies* M *if, and only if, it satisfies* N.

A proof is given in §2. Nonexpansiveness lies at the heart of the present paper. It implies that all trajectories are asymptotically equivalent (see (15)). We shall use this to define functionals which are independent of the starting conditions or the trajectory taken (Lemmas 3.1 and 4.1). We shall further show that these functionals encode much information about the dynamical behaviour of topical functions, in particular about the existence of fixed points, or equilibria, (Corollary 3.1 and Theorem 4.2).

The usual notion of a fixed point, $F(x) = x$, is inappropriate for discrete event systems. In the scenario above the events would have to occur infinitely fast! Definition 3.2 will allow for the possibility that there is some $h \in \mathbb{R}$ such that $F_i(x) = x_i + h$ for all $0 \leq i \leq n$. This is mathematically appropriate in the light of property H and is a reasonable model of equilibrium for a discrete event system: each event occurs at the same rate. The number h amounts to an additive eigenvalue and will be recovered through the cycle time vector, one of the functionals mentioned above.

The results of §3 and §4 suggest a new perspective on the study of fixed points of nonexpansive functions. We recall that for a contraction, for which $\|F(x) - F(y)\| \leq \alpha\|x - y\|$ with $0 < \alpha < 1$, the Banach Contraction Principle tells us that there is a unique fixed point to which all trajectories converge at an exponential rate, [27, Chapter 2]. When the function is only nonexpansive, so that $\alpha = 1$, the existence of fixed points is a classical problem of functional analysis. Work on this has developed in two main directions. One, arising out of the work of Browder and others in the 1960s, seeks geometric conditions (usually convexity properties) on the ambient Banach space which imply that every nonexpansive function has a fixed point, [27]. The other, arising originally from attempts to extend the Brouwer fixed point theorem, has sought properties of the function (such as the non-vanishing of the Leray-Schauder degree) which imply the existence of a fixed point, [10].

The present paper shows that dynamical properties, in the form of averages over trajectories, also give information on the existence of fixed points (see Corollary 3.1). It remains unclear, at present, to what extent this is special to the theory of topical functions and the ℓ^∞ norm or is part of a broader approach to the classical fixed point problem for nonexpansive functions.

The ℓ^∞ norm is well known to have singular properties. It is a polyhedral norm: the unit ball is a polyhedron and hence a combinatorial object. This discreteness is particularly appropriate to the study of discrete event systems. It also limits the cyclical behaviour that a system can have. A point $x \in \mathbb{R}^n$ is said to be a periodic point of F with period p if $F^p(x) = x$ and $F^k(x) \neq x$ for all $0 < k < p$. The following result is due independently to Sine and Nussbaum.

Theorem 1.1 ([48, 56]) *There exists $M(n) \in \mathbb{N}$, depending only on the dimension n, such that if $F : \mathbb{R}^n \to \mathbb{R}^n$ is any function satisfying* N *and p is the period of any periodic point of F, then $p \leq M(n)$.*

This should be contrasted with the case of the ℓ^2 (Euclidean) norm. Even when $n = 2$ there are rotations (which, being isometries, are necessarily nonexpansive) having periodic points with arbitrarily large periods.

Blokhuis and Wilbrink have given an elegant, short proof that $M(n) \leq (2n)^n$, [9]. By taking the vertices of the unit ball in the ℓ^∞ norm as the points of a periodic orbit, and by using the Aronszajn-Panitchpakdi theorem, [1], to construct a nonexpansive map, it is easy to show that $2^n \leq M(n)$. Nussbaum has conjectured that 2^n is best possible and Lyons and Nussbaum have shown this for $n \leq 3$, [41]. The Nussbaum conjecture remains an important open problem and a more detailed discussion of the literature surrounding it can be found in [45]. For topical functions, a much smaller bound is thought to exist, as discussed further in §2.1.3.

We were originally led to study topical functions because they arose naturally from attempts to model certain discrete event systems, [31]. However, as pointed out above, it is not the case that all discrete event systems, or even most discrete event systems, can be modelled in this way.

Attempts to study discrete event systems are haunted by the bewildering complexity of real engineering practice. So many additional features must be incorporated to describe specific engineering situations that mathematical generality is all too often lost. While this may still have value for specific problems, it sacrifices the ultimate goal of identifying general theorems that engineers can use in their daily work. We take a different approach here. The mathematical understanding of the dynamics of discrete event systems is extremely incomplete. The strategic need to improve this situation outweighs, in the long term, the tactical gains to be had in modelling individual systems. In the work described here we limit our attention to some simple assumptions, which nevertheless occur in practice, and try to answer the kinds of questions that confront engineers.

The next section introduces the main examples that will be studied in this paper: the affine hierarchy, and, at the other extreme, nonnegative matrices. At the urging of the reviewers, a further subsection of additional examples, §2.3, has also been included. §3 introduces the cycle time vector and sketches the proof of the main result on the affine hierarchy, Theorem 3.2. §4 speculates on how this result can be extended to nonnegative matrices and general topical functions.

The results discussed here draw on the work of the author and several collaborators, in particular Stéphane Gaubert, Michael Keane and Colin Sparrow. It is a pleasure to thank them as well as the many others who have contributed to the development of this area. The comments of the editors and of three anonymous reviewers are also gratefully acknowledged; their perceptive and helpful remarks led to a number of improvements. This work was partially supported by the European Commission through the research network ALAPEDES (Algebraic Approach to Performance Evaluation of Discrete Event Systems).

2 Examples and applications

We begin with some notation and then give a short proof of Proposition 1.1. We then exhibit a series of examples, summarising along the way the role that some of them play in the applications to discrete event systems. These examples provide the raw material for the discussions in §3 and §4.

We use throughout this paper the following vector-scalar convention: if, in a binary operation or a relation, a vector and a scalar appear together, the corresponding operation is applied to, or the corresponding relation is taken to hold, on each component of the vector. For instance, if $x \in \mathbb{R}^n$ and $h \in \mathbb{R}$, then $x + h$ will denote the vector $(x_1 + h, \cdots, x_n + h)$. This allows us to restate the property of homogeneity more succinctly as follows:

$$F(x + h) = F(x) + h\,.$$

Similarly, $x \leq h$, means $x_i \leq h$ for all $1 \leq i \leq n$. The symbol h always stands for a real number.

The standard partial order on $\mathbb{R}$ is denoted by $a \leq b$. We use infix operators for the lattice operations of least upper bound and greatest lower bound: $a \vee b = \mathrm{lub}(a, b)$ and $a \wedge b = \mathrm{glb}(a, b)$. The same notations are used for partially ordered sets derived from $\mathbb{R}$, such as the function space $X \to \mathbb{R}$, where the partial order is taken pointwise: $f \leq g$ if, and only if, $f(x) \leq g(x)$ for all $x \in X$. If $\mathbb{R}^n$ is identified with $\{1, \cdots, n\} \to \mathbb{R}$, then this corresponds to the usual product ordering on $\mathbb{R}^n$.

We assume that $+$ always has higher binding than either $\vee$ or $\wedge$. Hence, $x_1 + 2 \vee x_2 - 1 = (x_1 + 2) \vee (x_2 - 1)$.

It is helpful to pick out the following functions: $\mathsf{t}, \mathsf{b} : \mathbb{R}^n \to \mathbb{R}$ (top and bottom, respectively), where

$$\begin{array}{rcl} \mathsf{t}(x) & = & x_1 \vee \cdots \vee x_n \\ \mathsf{b}(x) & = & x_1 \wedge \cdots \wedge x_n \,. \end{array}$$

Note that $\|x\| = \mathsf{t}(x) \vee -\mathsf{b}(x)$ and that both t and b satisfy the properties H and M. In particular, addition distributes over both $\vee$ and $\wedge$: $\mathsf{t}(x+h) = \mathsf{t}(x)+h$ and $\mathsf{b}(x+h) = \mathsf{b}(x)+h$.

We make extensive use of the vector-scalar convention in the following argument, which follows that given in [34, §1].

Proof (of Proposition 1.1): Let $F : \mathbb{R}^n \to \mathbb{R}^n$ satisfy H. Assume first that F also satisfies M. Choose $x, y \in \mathbb{R}^n$. Since $y + \mathsf{b}(x - y) \leq x \leq y + \mathsf{t}(x - y)$ it follows by M and H that $F(y) + \mathsf{b}(x - y) \leq F(x) \leq F(y) + \mathsf{t}(x - y)$. Hence,

$$\mathsf{b}(x - y) \leq F(x) - F(y) \leq \mathsf{t}(x - y) \tag{1}$$

and so $\|F(x) - F(y)\| \leq \|x - y\|$ as required.

Now assume that F satisfies N. It is simplest to show first that (1) must hold. So choose $x, y \in \mathbb{R}^n$. Let $h = \mathsf{t}(y-x)$ and $z = x+h$. Note that $y \leq z$ so that $\|z - y\| = \mathsf{t}(z-y)$. By H and N, $F(x)-F(y) = F(z)-F(y)-h \leq \mathsf{t}(z-y)-h = \mathsf{t}(x-y)$. Since $\mathsf{t}(x) = -\mathsf{b}(-x)$ and x, y were chosen arbitrarily, it is easy to see that the other inequality, $\mathsf{b}(x - y) \leq F(x) - F(y)$, must also hold, thereby showing (1).

Now suppose that $x \leq y$. Then $0 \leq \mathsf{b}(y - x) \leq F(y) - F(x)$ and so $F(x) \leq F(y)$. This completes the proof.

As the proof shows, rather more is true that is stated in the result of Crandall and Tartar; see [34, Proposition 1.1] for a more detailed account.

We can now begin to explore the space of topical functions. Let $\mathsf{Top}(n, n)$ denote the set of topical functions in dimension n. It is easy to construct simple examples, such as coordinate substitutions.

Definition 2.1 *A function $F : \mathbb{R}^n \to \mathbb{R}^n$ is said to be simple if each component F_i has the form $F_i(x) = x_j$ for some $1 \leq j \leq n$. The set of simple functions in dimension n is denoted $\mathsf{Sim}(n, n)$.*

Simple functions do not have to be permutations: the same x_j may be used for different x_i. To put it another way, the matrix corresponding to this linear function has a 1 in each row but not necessarily in each column.

It is also easy to see that a number of operators preserve the properties H and M.

Proposition 2.1 *Suppose that $F, G \in \mathsf{Top}(n,n)$. Choose $u \in \mathbb{R}^n$ and choose $\lambda, \mu \in \mathbb{R}$ such that $0 \leq \lambda, \mu$, $\lambda + \mu = 1$. Then $-F(-x), F+u$, $F \vee G$, $F \wedge G$, $\lambda F + \mu G$, $FG \in \mathsf{Top}(n,n)$.*

We now have a number of ways to construct classes of topical functions by starting with simple functions and closing under some sequence of operators from Proposition 2.1. It is helpful to have some notation for this, which we take from [23]. Let $\mathcal{A}$ denote the following set of operator symbols, $\mathcal{A} = \{\max, \min, +, \mathbb{E}\}$. If $S \subseteq \mathsf{Top}(n,n)$ then define the following constructions which, by Proposition 2.1, all yield further subsets of $\mathsf{Top}(n,n)$.

$$\begin{aligned}
\max(S) &= \{ \bigvee_{F \in A} F \mid A \subseteq S, \text{ A finite} \} \\
\min(S) &= \{ \bigwedge_{F \in A} F \mid A \subseteq S, \text{ A finite} \} \\
\mathbb{E}(S) &= \{ \sum_{F \in A} \lambda_F F \mid A \subseteq S, \text{ A finite}, \ 0 \leq \lambda_F, \ \textstyle\sum_{F \in A} \lambda_F = 1 \} \\
+(S) &= \{ F + u \mid F \in S, \ u \in \mathbb{R}^n \}
\end{aligned}$$

If $\alpha_1, \cdots, \alpha_p$ is a sequence of operators symbols with $\alpha_i \in \mathcal{A}$, then the notation $(\alpha_1, \cdots, \alpha_p)$ will denote the subset $\alpha_1(\alpha_2(\cdots(\mathsf{Sim}(n,n))\cdots)) \subseteq \mathsf{Top}(n,n)$.

2.1 The affine hierarchy

We now examine the simpler classes of topical functions arising from Proposition 2.1, with specific examples mostly drawn from dimension 2. We then show how these can be viewed as elements of a hierarchy.

2.1.1 $(\max, +)$: matrices over the max-plus semiring

$$\begin{aligned}
F_1(x_1, x_2) &= x_1 + 0.2 \vee x_2 - 1 \\
F_2(x_1, x_2) &= x_1 + 1.6
\end{aligned} \tag{2}$$

The standard properties of $\vee$ can be used to reduce all elements of $(\max, +)$ to the general form exemplified above. Consider now the following trick, whose origins go back at least as far as Cuninghame-Green, [17] (see also [18] for historical references). Adjoin the element $-\infty$ to $\mathbb{R}$ and redefine the operations of addition and multiplication to be maximum and addition, respectively. Note, as mentioned above, that addition distributes over maximum and that, furthermore, $-\infty$ acts as a zero for maximum. The resulting semiring is called the max-plus semiring and denoted $\mathbb{R}_{\max}$. It is easy to see that (2) can now be rewritten as a matrix equation over $\mathbb{R}_{\max}$: $F(x) = Ax$, where x is now a column vector and A is the max-plus matrix

$$A = \begin{pmatrix} 0.2 & -1 \\ 1.6 & -\infty \end{pmatrix}. \tag{3}$$

More precisely, there is a one-to-one correspondence between elements of $(\max, +)$ in dimension n and $n \times n$ matrices over $\mathbb{R}_{\max}$ satisfying the following non-degeneracy condition:

$$\forall 1 \leq i \leq n, \ \exists 1 \leq j \leq n, \ \text{such that} \ A_{ij} \neq -\infty\,. \tag{4}$$

In the remainder of this paper we shall sometimes use max-plus notation (so that customary symbols or abbreviations will have their max-plus meanings) and sometimes ordinary notation (customary symbols have their customary meanings); the context will make clear which interpretation is intended.

A great deal is now understood about the spectral theory—the theory of eigenvectors and eigenvalues—of matrices over $\mathbb{R}_{\max}$. Part of the impetus for studying this has come from the realisation that eigenvalues of max-plus matrices give performance measures for discrete event systems. This is the most highly developed area of application and we outline some of this material here with references to the literature. There is a suprisingly close analogy between the spectral theory of max-plus matrices and that of nonnegative matrices. The reasons behind this are mysterious and apparently related to the asymptotics of large deviations. See [30, §6.5] for more details.

If A is an $n \times n$ matrix over $\mathbb{R}_{\max}$, then $x \in (\mathbb{R}_{\max})^n$ is said to be an eigenvector of A with eigenvalue $\lambda \in \mathbb{R}_{\max}$, if $Ax = \lambda x$. For purposes of illustration, assume that A satisfies (4), so that $A : \mathbb{R}^n \to \mathbb{R}^n$, and restrict attention to real eigenvectors: eigenvectors lying in $\mathbb{R}^n$. Suppose that $x, y \in \mathbb{R}^n$ are two such real eigenvectors of A with eigenvalues λ and μ respectively. By matrix multiplication we see that $A^k x = \lambda^k x$ and $A^k y = \mu^k y$. By property N, however, $\|A^k x - A^k y\| \leq \|x - y\|$. Rewriting this in ordinary notation, we see that $\|(k\lambda + x) - (k\mu + y)\| \leq \|x - y\|$ for any k. Dividing throughout by k and letting $k \to \infty$, we see that $\lambda = \mu$. Any two real eigenvectors have the same eigenvalue.

Use of the nonexpansiveness property in this manner—to show that certain functionals are well defined and independent of initial conditions—will recur throughout this paper (see Lemma 3.1 and Lemma 4.1). Similar results hold for the other eigenvalues, corresponding to eigenvectors in $(\mathbb{R}_{\max})^n$, but different arguments are needed. The full spectral theory, applicable to arbitrary eigenvectors, is described by Wende *et al* in [60] and independently in Gaubert's thesis, [22].

What can be said about the eigenvalue corresponding to a real eigenvector? Unlike nonnegative matrix theory, in which only bounds are known for the eigenvalues, [44, Chapter 2], there are formulae for the eigenvalues of a max-plus matrix. These emerge from the close relationship between matrices and graphs.

The precedence graph of A, denoted $\mathcal{G}(A)$, is the directed graph with labelled edges which has nodes $\{1, \cdots, n\}$ and an edge from j to i if, and only if, $A_{ij} \neq -\infty$. The label on this edge is then the real number A_{ij}. (The opposite convention for the direction of edges is sometimes used.) The existence of an edge from j to i is denoted $i \leftarrow j$. A path in this graph has the usual meaning of a chain of directed edges: a path from i_m to i_1 is a sequence of nodes $i_1, \cdots, i_m$ such that $1 < m$ and $i_j \leftarrow i_{j+1}$ for $1 \leq j < m$. A circuit is a path which starts and ends at the same node: $i_1 = i_m$. A circuit is elementary if the nodes $i_1, \cdots, i_{m-1}$ are all distinct. The matrix A is said to be irreducible if $\mathcal{G}(A)$ is strongly connected: there is a path connecting any pair of distinct nodes. Equivalently, A is irreducible if there is no permutation of the rows and columns which brings it into upper triangular block form. The matrix of example (3) is irreducible.

The weight of a path p, $|p|_{\mathsf{w}}$, is the product in $\mathsf{R}_{\max}$ of the labels on the edges in the path, or, in ordinary notation:

$$|p|_{\mathsf{w}} = \sum_{j=1}^{m-1} A_{i_j i_{j+1}} \,.$$

Matrix multiplication has the following interpretation in terms of path weights: A^s_{ij} is the maximum weight among all paths of length s from j to i. Hence problems of optimal path finding in graphs can be treated by methods of matrix algebra over $\mathsf{R}_{\max}$, [4, 13, 28].

The length of a path, $|p|_\ell$, is the number of edges in the path: $|p|_\ell = m - 1$. If g is a circuit, its cycle mean, denoted $\mathsf{m}(g)$, is defined, in ordinary notation, by $\mathsf{m}(g) = |g|_{\mathsf{w}}/|g|_\ell$. Let $\mu(A) \in \mathsf{R}_{\max}$ denote the maximum cycle mean:

$$\mu(A) = \max\{\mathsf{m}(g) \mid g \text{ a circuit}\} \,. \tag{5}$$

This is well defined: by virtue of (4), $\mathcal{G}(A)$ has at least one circuit, and although it therefore has infinitely many, it is easy to see that only the elementary ones are needed to determine $\mu(A)$. For the matrix of example (3), $\mu(A) = 0.3$.

Proposition 2.2 ([2, Theorem 3.23]) *Let A be any $n \times n$ matrix over $\mathsf{R}_{\max}$. The eigenvalue of any real eigenvector is $\mu(A)$ and this is the largest eigenvalue of A. Furthermore, if A is irreducible, it has a real eigenvector.*

$\mu(A)$ is sometimes called the spectral radius or Perron root of A because of the close analogy between Proposition 2.2 and the Perron-Frobenius theorem for nonnegative matrices. Proposition 2.2 is one of the basic results of max-plus spectral theory and has been rediscovered so many times that it is hard to ascribe priority to any particular source. The stated reference is to one of the standard texts in the subject.

Max-plus matrices can be used to describe the time evolution of discrete event systems in which the timing constraints are all maximum ones. These are the timed versions of systems in which the causal relationships between events are represented by a partially ordered set: the AND causality between events being transformed naturally into a maximum timing constraint. A well-known model with this property is that of event graphs (sometimes called marked graphs). These are Petri nets in which each place is the input to at most one transition and the output to at most one transition. This leads to the observation that *"timed event graphs are max-plus linear systems"*, [2, Theorem 2.58]: the evolution of a timed event graph can be described by a linear equation over $\mathsf{R}_{\max}$ of the form

$$x(k) = A_0 x(k) + A_1 x(k-1) + \cdots + A_s x(k-s) \,.$$

The vector $x(k) \in \mathsf{R}^n$ describes the times at which the n transitions in the event graph fire for the k-th time, as in the scenario described in the Introduction. This approach and its consequences are described further in [2, 15, 29].

Because of the widespread importance of event graphs and related models, many special cases and *ad hoc* results about their timing behaviour have appeared in the literature, [12, 20, 50, 51, 52]. More recently, max-plus matrix methods have been used more directly: by Ferrari and Montanari in developing cost calculi for communicating processes, [21], and by Hulgaard *et al* in studying the time separation of events problem, [35]. A recurring theme in some of this work is the construction of performance measures which turn out to be nothing other than the spectral radius, $\mu(A)$, of the underlying max-plus matrix. We shall recover this performance measure for general topical functions in the guise of the cycle time vector of §3.

The max-plus semiring is an example of a dioid, or idempotent semiring: a semiring in which addition satisfies the idempotent law, $a + a = a$. Another example well known to computer scientists is the dioid of formal languages over an alphabet A, in which addition corresponds to union of languages and multiplication to concatenation. The subject of idempotency, which encompasses both such examples, is discussed further in [30].

2.1.2 $(\min, +)$: matrices over the min-plus semiring

This is dual to the case of $(\max, +)$. The min-plus semiring, $\mathsf{R}_{\min}$, is the set $\mathsf{R} \cup \{+\infty\}$ with addition and multiplication defined as minimum and addition, respectively. The map $x \to -x$ establishes the duality between $\mathsf{R}_{\max}$ and $\mathsf{R}_{\min}$ and is also an isomorphism of idempotent semirings.

2.1.3 $(\min, \max, +)$: min-max functions

$$\begin{array}{rcl} F_1(x_1, x_2) & = & (x_1 - 2 \vee x_2 + 1) \wedge (x_1 - 3 \vee x_2 + 3) \wedge (x_1 - 4 \vee x_2 + 2) \\ F_2(x_1, x_2) & = & (x_1 - 2 \wedge x_2 + 1) \vee (x_1 \wedge x_2 - 2) \end{array} \tag{6}$$

The properties of $\vee$ and $\wedge$ can be used to reduce any element of $(\min, \max, +)$ to the general form above, where there is no finite bound on the number of terms which may appear. Topical functions of this kind are called min-max functions. Special cases of them were considered by Olsder in [49] while min-max functions themselves were introduced in [32].

Min-max functions appear in analysing the timing behaviour of digital circuits. For instance, Sakallah, Mudge and Olukotun (SMO) developed a model for analysing circuits containing storage latches controlled by a central clock, [55]. In such circuits, the incoming signal at a latch must arrive and stabilise within a certain setup time in order for the signal to be correctly stored when the latch opens. The opening and closing of the latches is controlled through a clocking schedule, which allows overlapping of latch operation so as to optimise performance. Once a clocking schedule has been chosen, it must be verified to meet the setup constraints.

The SMO model can be formulated as follows, [57]. Assume that the latches are numbered from 1 to n and that $j \to i$ is the "fans out to" relation on latches. That is, $j \to i$, if, and only if, there is a path of combinational logic from the output of j to the input of i. Define the min-max functions $D, d : \mathsf{R}^{n+1} \to \mathsf{R}^{n+1}$ by the following equations:

$$\begin{array}{rcll} D_i(x) & = & (\vee_{j \to i}\{x_j + \Lambda_{j,i}\}) \wedge (x_{n+1} + B_i) & \text{for } 1 \leq i \leq n \\ D_{n+1}(x) & = & x_{n+1} & \\ d_i(x) & = & (\wedge_{j \to i}\{x_j + \lambda_{j,i}\}) \wedge (x_{n+1} + B_i) & \text{for } 1 \leq i \leq n \\ d_{n+1}(x) & = & x_{n+1} & \end{array}$$

where $\Lambda_{i,j}$, $\lambda_{i,j}$ and B_i are constants defined by the clocking schedule and the minimum and maximum delays through the combinational logic, [57, Figure 2]. x_{n+1} is a dummy variable whose only purpose is to make it clear that D and d are genuine min-max functions. While d is min only, D is min-max.

It can be shown that if $D(x) = x$ then $x_i - x_{n+1}$ is the latest signal departure time from latch i, [57, Figure 2]. Similarly, if $d(x) = x$ then $x_i - x_{n+1}$ is the earliest signal departure time from latch i. If these fixed points can be found and the arrival times can be shown to satisfy the setup constraints, then the clock schedule is verified. Hence the problem of clock schedule verification can be reduced to that of finding a fixed point for a min-max function. See [31] for further discussion.

Another example of the use of min-max functions is provided by the work of Hulgaard, Burns, Amon and Borriello, [35]. If t_a^k denotes the time of k-th occurrence of event a in a discrete event system, then the time separation of events problem asks for bounds on the separation, $t_a^k - t_b^l$, between the k-th occurrence of a and the l-th occurrence of b. The data for this kind of problem consists not of individual delays but instead of delay bounds, $[u, v]$, where $0 \leq u \leq v < +\infty$. This is commonplace in hardware systems, as in the clock schedule verification problem above, where manufacturers provide minimum and maximum propagation delays in component specifications. The presence of both minimum and maximum constraints leads naturally to a min-max formalism and Hulgaard *et al* make use of an algebra of min-max functions to calculate exact bounds for the time separation problem.

Min-max functions play a useful role within the theory of topical functions. The following are unpublished results of Gunawardena and Sparrow.

Proposition 2.3 *Let $F : \mathsf{R}^n \to \mathsf{R}^n$ be any topical function and let $U \subseteq \mathsf{R}^n$ be any finite set of vectors. There exists a min-max function, $H : \mathsf{R}^n \to \mathsf{R}^n$ such that $F \leq H$ and $F(x) = H(x)$ for all $x \in U$.*

Proof: Consider first the case when $U = \{u\}$. Let $H(u)(x) = F(u) + \mathsf{t}(x - u)$ and note that, as a function of $x \in \mathsf{R}^n$, H is a max-only function. Since $x - u \leq \mathsf{t}(x - u)$, it follows from properties H and M that $F(x) \leq H(u)(x)$. Clearly, $F(u) = H(u)(u)$. Now suppose that $U = \{u^1, \cdots, u^m\}$. Then $\bigwedge_{1 \leq j \leq m} H(u^j)(x)$ is a min-max function which satisfies the conclusions of the Proposition.

It follows that any finite trajectory of a topical function, $x, F(x), \cdots, F^p(x)$ is also the trajectory of some min-max function. In particular, if x is a periodic point, with $F^p(x) = x$, then there is a min-max function with the same period. Hence to determine the maximum period of a topical function it is sufficient to consider only min-max functions.

A lower bound for this can be established by the following elementary construction. Let $u^1, u^2, \cdots, u^m \in \{0, 1\}^n$ be any sequence of pairwise mutually incomparable binary vectors. In other words, an antichain in this distributive lattice. By convention, let $u^{m+1} = u^1$. For each $1 \leq j \leq m$, define the Boolean function $h(j) : \mathsf{R}^n \to \mathsf{R}$ by

$$h(j)(x_1, \cdots, x_n) = \bigwedge_{1 \leq k \leq n,\ (u^j)_k = 1} x_k \,.$$

Because the vectors u^j are pairwise mutually incomparable, it follows that $h(j)(u^i) = \delta_{ij}$.

Hence the min-max function $H : \mathsf{R}^n \to \mathsf{R}^n$ defined by

$$H_i(x) = \bigvee_{1 \leq j \leq m,\ (u^{j+1})_i = 1} h(j)(x)$$

satisfies $H(u^j) = u^{j+1}$ for $1 \leq j \leq m$, so that $u^1, \cdots, u^m$ is a periodic orbit of H with period m.

Sperner's Theorem shows that the size of a maximal antichain in $\{0,1\}^n$ is the binomial coefficient ${}^nC_{[n/2]}$, [37, Theorem 3.1.1], which gives a lower bound on the maximum period of a topical function. We conjecture that this is also an upper bound and have shown this to be true for $n \leq 3$. The construction of periodic orbits for topical functions is a purely combinatorial problem. The method of Proposition 2.3 can be used to show the following, where we use the same conventions as before.

Lemma 2.1 *In order that the sequence of vectors $u^1, \cdots, u^m \in \mathsf{R}^n$ is a periodic orbit of some topical function F, so that $F(u^j) = u^{j+1}$ for $1 \leq j \leq m$, it is necessary and sufficient that, for all $1 \leq j, k \leq m$, $\mathsf{t}(u^j - u^k) = \mathsf{t}(u^{j+1} - u^{k+1})$.*

This suggests that establishing an upper bound for the periods of topical functions is of comparable difficulty to doing so for nonexpansive functions, [9].

2.1.4 (E): row stochastic matrices

Suppose that $\{a, b, c, d\} \subseteq [0,1]$ and that $a + b = 1$ and $c + d = 1$. It is easy to verify that

$$\begin{pmatrix} a & b \\ c & d \end{pmatrix} = a\left[c\begin{pmatrix} 1 & 0 \\ 1 & 0 \end{pmatrix} + d\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}\right] + b\left[c\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} + d\begin{pmatrix} 0 & 1 \\ 0 & 1 \end{pmatrix}\right]$$

A glance at this should convince the reader of the following elementary observation, which is amusingly similar to Birkhoff's famous result on the structure of doubly stochastic matrices, [44, §5.3].

Lemma 2.2 *A matrix is row stochastic if, and only if, it is a finite convex combination of substitution matrices.*

It follows that (E) in dimension n is exactly the set of $n \times n$ row stochastic matrices.

2.1.5 $(\min, +, \mathsf{E})$: Bellman operators of Markov decision processes

Let U be a finite index set and, for each $u \in U$, let $c^u \in \mathsf{R}^n$ and A^u be a $n \times n$ row stochastic matrix. In the light of Lemma 2.2, the function

$$F(x) = \bigwedge_{u \in U} c^u + A^u x \tag{7}$$

gives the general form of an element in $(\min, +, \mathsf{E})$. Functions of this kind are well known in optimal control as the dynamic programming (Bellman) operators associated to Markov decision processes. U indexes the set of possible decisions. The choice of decision influences the transition probabilities, A^u, of moving between the n states of the process. Each decision comes with an associated state-dependent cost, $c^u \in \mathsf{R}^n$. $F_i(x)$ is the minimal expected cost of a single process step starting from state i, given that x_j is the cost of ending in state j. By Bellman's optimality principle, $F^k(x)$ gives the corresponding minimal expected cost associated to k process steps. A fixed point of F corresponds to an optimal cost vector, whose existence and calculation are important problems in decision theory, [6].

This completes our survey of the simpler examples arising from $\mathsf{Sim}(n,n)$ through repeated use of Proposition 2.1. On the face of it, there are many more complex functions arising from longer sequences of operator symbols. It is helpful to have a linear hierarchy in which all these functions eventually appear. To this end, define the sequence $\mathcal{A}^0 \subseteq \mathcal{A}^1 \subseteq \cdots \subseteq \mathsf{Top}(n,n)$ as follows.

$$\begin{array}{rcl} \mathcal{A}^0 & = & \mathsf{Sim}(n,n) \\ \mathcal{A}^i & = & \bigcup_{\alpha \in \mathcal{A}} \alpha(\mathcal{A}^{i-1}) \ \text{ for } 1 \leq i \\ \mathcal{A}^* & = & \bigcup_i \mathcal{A}^i \end{array}$$

The following result shows that this hierarchy collapses sooner than one might think and that many of the functions in $\mathcal{A}^*$ have already arisen in the examples above. The proof is straightforward but tedious and is left to the reader and [23, §2.2].

Proposition 2.4 ([23, Proposition 12]) $\mathcal{A}^* = \mathcal{A}^4 = (\min, \max, +, \mathsf{E})$.

Functions in $\mathcal{A}^*$ are piecewise affine: they consist of a finite number of affine pieces. Hence the phrase "affine hierarchy" to describe $\mathcal{A}^*$. This property plays an important role in the proof of Theorem 3.2.

We now turn to a quite different class of topical functions, which may be thought of as lying at the opposite extreme to the affine hierarchy within $\mathsf{Top}(n,n)$.

2.2 Functions on the positive cone

Let R^+ denote the positive reals. Let $\exp : \mathsf{R}^n \to (\mathsf{R}^+)^n$ and $\log : (\mathsf{R}^+)^n \to \mathsf{R}^n$ be defined componentwise: $\exp(x)_i = \exp(x_i)$ and $\log(x)_i = \log(x_i)$. These establish a bijective correspondence between R^n and $(\mathsf{R}^+)^n$. This correspondence is an isometry from R^n with the ℓ^∞ norm to $(\mathsf{R}^+)^n$ equipped with Thompson's metric (see §2.3), [46, Proposition 1.6]. Let $A : (\mathsf{R}^+)^n \to (\mathsf{R}^+)^n$ be any function on the positive cone and let $\mathcal{E}(A) : \mathsf{R}^n \to \mathsf{R}^n$ denote the function $\log(A(\exp))$. The functional $\mathcal{E}$ transports functions on the positive cone bijectively to functions on R^n. It is easy to see that $\mathcal{E}(AB) = \mathcal{E}(A)\mathcal{E}(B)$. In particular, $\mathcal{E}(A^k) = \mathcal{E}(A)^k$ so that the dynamic behaviour of A and $\mathcal{E}(A)$ are equivalent and interchangeable and the dynamics may be studied either on R^n or on $(\mathsf{R}^+)^n$.

If $x, y \in (\mathsf{R}^+)^n$, then $x \leq y$ will denote the product ordering on $(\mathsf{R}^+)^n$. The properties of monotonicity and homogeneity have obvious counterparts on $(\mathsf{R}^+)^n$. Let $A : (\mathsf{R}^+)^n \to (\mathsf{R}^+)^n$. It follows easily from the well-known properties of exp and log that $\mathcal{E}(A)$ satisfies H if, and only if, A satisfies

- $\forall x \in (\mathsf{R}^+)^n,\ \forall \lambda \in \mathsf{R}^+, \quad A(\lambda x) = \lambda A(x)$ HP

and that $\mathcal{E}(A)$ satisfies M if, and only if, A satisfies

- $\forall x, y \in (\mathsf{R}^+)^n, \quad x \leq y \ \Rightarrow\ A(x) \leq A(y)\,.$ MP

Nonexpansiveness in the ℓ^∞ norm in R^n corresponds to nonexpansiveness with respect to Thompson's metric in $(\mathsf{R}^+)^n$ (see §2.3) but this will not be needed here. We shall refer to functions $A : (\mathsf{R}^+)^n \to (\mathsf{R}^+)^n$ which satisfy HP and MP as topical functions on the positive cone, it being understood that $\mathcal{E}(A)$ is then a topical function in the strict sense. This correspondence between functions on R^n and functions on $(\mathsf{R}^+)^n$ immediately suggests a fresh source of topical functions.

2.2.1 Nonnegative matrices

Suppose that $A : (\mathsf{R}^+)^n \to (\mathsf{R}^+)^n$ is represented by a nonnegative matrix with respect to the standard basis. A given nonnegative matrix will define a function on the positive cone if, and only if, it satisfies a similar non-degeneracy condition to (4):

$$\forall i,\ \exists j, \text{ such that } A_{ij} \neq 0\,. \tag{8}$$

It follows from the discussion above that A is a topical function on the positive cone. Despite the equivalence between R^n and $(\mathsf{R}^+)^n$, $\mathcal{E}(A)$ looks quite unfamiliar when presented on R^n: the matrix

$$A = \begin{pmatrix} 1 & 2 & 3 \\ 0 & 4 & 0 \\ 5 & 0 & 6 \end{pmatrix}$$

becomes the topical function

$$\begin{array}{rcl} \mathcal{E}(A)_1 & = & \log(\exp(x_1) + 2\exp(x_2) + 3\exp(x_3)) \\ \mathcal{E}(A)_2 & = & \log(4) + x_2 \\ \mathcal{E}(A)_3 & = & \log(5\exp(x_1) + 6\exp(x_3))\,. \end{array}$$

The affine hierarchy and nonnegative matrices will be the two main classes studied in the remainder of this paper. However, the geography of the space of topical functions contains many other interesting, not to say exotic, examples. We briefly mention some of these to whet the reader's appetite for further exploration.

2.3 Additional examples of topical functions

Proposition 2.1 can be used as before on the positive cone to create new families of topical functions. This process once again yields examples that have been studied extensively in other fields. The Leontieff substitution systems of mathematical economics, for instance, arise as maxima of sets of nonnegative matrices, [11]. The asymptotics of these functions have been studied in [61].

In addition to the operations in Proposition 2.1, the positive cone reveals another obvious operation: if $A, B : (\mathsf{R}^+)^n \to (\mathsf{R}^+)^n$ are topical functions on the positive cone, then so is $A+B$. Note that $\mathcal{E}(A+B) \neq \mathcal{E}(A)+\mathcal{E}(B)$. Addition on the positive cone can now be used to construct new topical functions.

Means are a familiar class of homogeneous and monotone functions. For $x \in (\mathsf{R}^+)^n$, the arithmetic mean, $(x_1 + \cdots + x_n)/n$, geometric mean, $(x_1 \cdots x_n)^{1/n}$ and harmonic mean, $(1/x_1 + \cdots + 1/x_n)^{-1}$ all satisfy properties HP and MP as functions $(\mathsf{R}^+)^n \to \mathsf{R}$. So too do the classical p-norms, $(x_1^p + \cdots + x_n^p)^{1/p}$, for $1 \leq p \in \mathsf{R}^+$. They can hence all be used as the components of topical functions. Nussbaum brings these together in the following way, [47, Chapter 2]: let $r \in \mathsf{R}$ and let $\sigma \in (\mathsf{R}^+)^n$ be a discrete probability measure, so that $\sigma_1 + \cdots + \sigma_n = 1$. The function $m_{(r,\sigma)} : (\mathsf{R}^+)^n \to \mathsf{R}^+$ defined by

$$m_{(r,\sigma)} = \begin{cases} (\sigma_1 x_1^r + \cdots + \sigma_n x_n^r)^{1/r} & \text{if } r \neq 0 \\ x_1^{\sigma_1} \times \cdots \times x_n^{\sigma_n} & \text{if } r = 0 \end{cases}$$

is seen to satisfy properties HP and MP and to include all the means and norms mentioned above. (The choices used here make $m_{(r,\sigma)}(x)$ continuous at $r = 0$ for fixed x and σ.) Any function $(\mathsf{R}^+)^n \to (\mathsf{R}^+)^n$ each of whose components is of the form $m_{(r,\sigma)}$ will be a topical function on the positive cone. By closing the resulting set under scalar multiplication, addition and composition, an interesting class of topical functions emerges whose fixed point behaviour is still not fully understood, [47, Chapter 2]. Functions of this kind arise in population biology (see the extensive references in Nussbaum's paper) where the existence of fixed points is an important problem.

If A is a $n \times n$ nonnegative matrix, do there exist positive diagonal matrices, D_1 and D_2, such that $D_1 A D_2$ is row and column stochastic? This so-called DAD problem, and its generalisation to specified row and column sums, arises in many applications, such as graph enumeration and contingency tables in statistics, and there is a large literature associated with it, [47, Chapter 4]. Let $D : (\mathsf{R}^+)^n \to (\mathsf{R}^+)^n$ denote the function $D_i(x) = 1/x_i$. Menon and Schneider showed that there is a positive answer to the question of rescaling A if, and only if, the topical function DA^tDA has a fixed point in $(\mathsf{R}^+)^n$, [43]. DAD operators of this kind have been studied by Nussbaum using methods of nonlinear analysis, [47, Chapter 4] and Katirtzoglou has shown the existence of the cycle time vector (see § 3), [36].

Returning to R^n, the Markov decision process of §2.1.5 may be considered as a simplified stochastic game. The latter (or, at least, the finite, two-person, zero-sum, version of the latter) is a decision process with 2 players in which, at each step, the players conduct a zero-sum game in which the choice of strategies influences both the transition probabilities and the costs to one player (and the corresponding payoffs to the other). For more information on game theory see, for instance, [59]. The dynamic programming operator for the stochastic game takes the form

$$F(x) = \bigwedge_{u \in U} \bigvee_{v \in V} c^{uv} + A^{uv} x \tag{9}$$

where U is the simplex of mixed strategies (the compact, convex set of probability measures on the finite set of pure strategies) for the player who is charged the costs, V is the simplex of mixed strategies for the player who receives the payoffs, c^{uv} is the vector of costs and A^{uv} is the matrix of transition probabilities. The Markov decision process of §2.1.5 can now be seen as a stochastic game in which the player who gets the payoffs is reduced to playing the same unique strategy at each step. The crucial difference is that the sets U and V are no longer finite. Nevertheless, sup and inf over any set of parameters, when they remain finite, are monotone operators over which addition distributes. Hence $F(x)$ is a topical function, albeit one which is far from being in the affine hierarchy. There is a large literature on stochastic games. Of particular interest, in the light of the ideas developed in §3 and §4, is the work of Bewley and Kohlberg, who have made a deep study of the asymptotics of F, [7, 8].

The use of sup and inf over parameter spaces, as in (9), is another useful mechanism for constructing topical functions.

The last example of this subsection leads into uncharted waters. There are other cones beside the positive cone and analogues of topical functions exist on these. For the purposes of this paragraph, a cone will be taken to be a closed, convex subset K of a normed linear space V, such that $\lambda x \in K$ whenever $x \in K$ and $\lambda \in \mathsf{R}^+$. It will also be assumed to be pointed: if $x \in K$ and $-x \in K$ then $x = 0$. The nonnegative vectors in R^n are then a cone in this sense. For $x, y \in V$, define $x \leq_K y$ if $y - x \in K$. This defines a partial order, the cone order, on V, for which the pointedness of the cone is essential. The cone order on the nonnegative cone is the product ordering on R^n. There is, furthermore, a natural metric on the components of K. A component is here an equivalence class of vectors in K under the relation of comparability: $0 \neq x, y \in K$ are comparable if there exist $\alpha, \beta \in \mathsf{R}^+$ such that

$$\alpha x \leq y \leq \beta x \,. \tag{10}$$

$(\mathsf{R}^+)^n$ is one of the components of the nonnegative cone. If x and y are comparable, so that (10) holds, let $m(y/x) = \inf\{0 < \beta \mid y \leq \beta x\}$ and define the Thompson metric, $d(x, y)$, by

$$d(x, y) = \max(\log(m(y/x), \log(m(x/y))) \,.$$

On the interior component, $(\mathsf{R}^+)^n$, of the nonnegative cone, the Thompson metric corresponds to the ℓ^∞ norm under the bijection of §2.2: if $x, y \in \mathsf{R}^n$, $\|x - y\| = d(\exp(x), \exp(y))$. All the ingredients are in place to generalise the characteristic properties H, M and N of topical functions. Nussbaum has made a deep and extensive study of functions of this kind, [46, 47]. It remains a tantalising open question whether the ideas surveyed in §3 and §4 extend in any useful way to this much broader setting.

Generality often brings conceptual simplification. In this case there are also significant applications which would benefit. The construction of diffusions on certain (finitely ramified) fractals gives rise to a monotone, homogeneous and nonexpansive function on a cone of Dirichlet (quadratic) forms associated to the fractal. This function is a renormalisation operator coming from the iterative construction of the diffusion over successive finite approximations to the fractal. For the diffusion to exist, the function must have a suitably nondegenerate fixed point. Space precludes a precise description here but Sabot's paper, which makes explicit use of the topical properties, provides a good starting point into this literature, [54].

This completes the discussion of examples of topical functions. In addition to the natural ones seen so far there are many apparently pathological ones, as, for instance, the examples constructed by Gunawardena and Keane in [34] (see Theorem 3.1 below). The definitive natural history of topical functions remains to be written.

3 Cycle times and fixed points

The examples and applications discussed in the previous section reveal two related general questions. First, if a topical function represents the time evolution of a discrete event system then how can the performance of the system be measured? Second, under what circumstances does a topical function have a fixed point? The main result of this section is Theorem 3.2 which gives a detailed answer to these questions for functions in $\mathcal{A}^*$.

Suppose that $F : \mathsf{R}^n \to \mathsf{R}^n$ is a topical function which models a discrete event system under the scenario described in the Introduction. The delay between event occurrences can be measured by $F(x) - x$. If this is averaged over several occurrences, it yields

$$\frac{(F^k(x) - F^{k-1}(x)) + \cdots + (F(x) - x)}{k} = \frac{F^k(x) - x}{k}$$

which reduces asymptotically to $\lim_{k\to\infty} F^k(x)/k$, provided the limit exists. Assume for the moment that it does exist and that its value is $\chi \in \mathsf{R}^n$. This measures the asymptotic average delay between event occurrences assuming the system is started at the times $x \in \mathsf{R}^n$. What happens at other starting times? Choose $y \in \mathsf{R}^n$ and $\epsilon > 0$. We may choose k so large that $\|y - x\|/k \leq \epsilon/2$ and $\|F^k(x)/k - \chi\| \leq \epsilon/2$. Then, by nonexpansiveness,

$$\|F^k(y)/k - \chi\| \leq \|(F^k(y) - F^k(x))/k\| + \|(F^k(x)/k - \chi)\| \leq \|y - x\|/k + \epsilon/2 \leq \epsilon$$

for all sufficiently large k. It follows that $\lim_{k\to\infty} F^k(y)/k = \chi$. We have proved

Lemma 3.1 *Let $F \in \mathsf{Top}(n, n)$. If $\lim_{k\to\infty} F^k(x)/k$ exists for some $x \in \mathsf{R}^n$, then it exists for every $x \in \mathsf{R}^n$ and has the same value.*

Definition 3.1 *The cycle time vector of a topical function, denoted $\chi(F)$, is defined to be $\lim_{k\to\infty} F^k(x)/k \in \mathsf{R}^n$, when this limit exists, and is undefined otherwise.*

Let X be a Banach space and $F : X \to X$ a nonexpansive map on X. A necessary and sufficient condition for $F^k(x)/k$ to converge for all F is that the dual space of X has a norm which is Fréchet differentiable, [39]. This condition does not hold for R^n with the ℓ^∞ norm, whose dual space is R^n with the ℓ^1 norm. For topical functions, the cycle time vector does not always exist and χ defines only a partial functional from $\mathsf{Top}(n, n)$ to R^n. However, all the examples of topical functions on R^n or $(\mathsf{R}^+)^n$ discussed in §2 can be shown to have cycle time vectors and examples for which it does not exist have to be constructed carefully.

Theorem 3.1 ([34, Theorem 3.1]) *Let $a_1, a_2, \cdots \in [0, 1]$ be any sequence of numbers drawn from the unit interval. There exists $F \in \mathsf{Top}(3, 3)$ such that*

$$F^k(0, 0, 0)_2 = a_1 + \cdots + a_k \, .$$

It follows, by suitably choosing the sequence $\{a_i\}$, that there are topical functions F for which $\chi(F)$ does not exist. It remains an important open problem to characterise those topical functions for which $\chi(F)$ does exist. At the present time, there is not even a reasonable conjecture regarding this.

The cycle time vector is a performance measure for discrete event systems under the scenario described in the Introduction. It is also the appropriate generalisation of the eigenvalue to a nonlinear context. To see this, it is helpful to first introduce fixed points. As mentioned in the Introduction, it is appropriate to broaden the usual definition.

Definition 3.2 *Let $F \in \mathsf{Top}(n, n)$. The vector $x \in \mathsf{R}^n$ is said to be a fixed point of F if there exists $h \in \mathsf{R}$ such that $F(x) = x + h$.*

If F has a fixed point $x \in \mathsf{R}^n$, then homogeneity implies that $F^k(x) = x + kh$. It follows that $\chi(F) = h$. Hence, any function that has a fixed point must also have a cycle time vector. This immediately gives examples where the cycle time vector exists and shows, moreover, that it is a natural generalisation of the eigenvalue for both max-plus matrices and nonnegative matrices. For the former, if A is a $n \times n$ matrix over $\mathsf{R}_{\max}$ satisfying the nondegeneracy condition (4), then a fixed point corresponds precisely to a real eigenvector of A: $x \in \mathsf{R}^n$ such that, in max-plus notation, $Ax = \lambda x$. It follows that $\chi(A) = \lambda$ and we know from Proposition 2.2 that $\lambda = \mu(A)$, the maximum cycle mean of A defined in (5). If A is a nonnegative matrix satisfying the nondegeneracy condition (8), then a fixed point of $\mathcal{E}(A)$ corresponds precisely to a positive eigenvector of A: $x \in (\mathsf{R}^+)^n$ such that, in the usual notation, $Ax = \lambda x$. It follows that $\log(x)$ is a fixed point of $\mathcal{E}(A)$ and that $\chi(\mathcal{E}(A)) = \log(\lambda)$. In both cases, it can be shown that the cycle time vector always exists, even when the function does not have a fixed point.

The existence of a fixed point implies a stronger constraint on the cycle time because of its vectorial nature: each component must have the same value. In the context of discrete event systems, an equilibrium can only exist if each event occurs, asymptotically on average, at the same rate. It is interesting to ask to what extent this is also a sufficient condition for the existence of a fixed point. Is it the case that $\chi(F) = h$ if, and only if, there exists $x \in \mathsf{R}^n$ such that $F(x) = x + h$? For an important class of topical functions, an even stronger result is true.

Definition 3.3 *Let $F \in \mathsf{Top}(n, n)$. The vector $x \in \mathsf{R}^n$ is said to be a generalised fixed point of F if there exists $v \in \mathsf{R}^n$ such that $F^k(x) = x + kv$ for all k.*

It is clear that if F has a generalised fixed point, then $\chi(F) = v$. However, because v is no longer a scalar, the iterative behaviour of F at x cannot be deduced from the homogeneity property. The definition of a generalised fixed point requires, in principle, an infinite amount of information about the trajectory starting from x.

Theorem 3.2 ([23, Theorem 15]) *Any function in $\mathcal{A}^*$ has a generalised fixed point.*

This result has a number of useful and interesting consequences.

Corollary 3.1 *If $F \in \mathcal{A}^*$ then $\chi(F)$ exists. Moreover, F has a fixed point if, and only if, $\chi(F) = h$ for some $h \in \mathsf{R}$.*

The problem of calculating $\chi(F)$ is not solved in general. However, for the class of min-max functions, Theorem 3.2 implies the positive solution of the Duality Conjecture, [24, Corollary 2], which yields a systematic method of calculation, albeit one of exponential complexity. The problem of calculating fixed points is also unsolved in general but for min-max functions an algorithm that works well in practice is described in [14, §2.3].

Theorem 3.2 is a special case of a beautiful result of Elon Kohlberg: any piecewise affine transformation on R^n, which is nonexpansive in some norm, must have an invariant half-line, [38, Theorem 2.1]. The proof relies on Farkas' Lemma on linear inequalities over ordered fields. At the time of first writing of the present paper, Kohlberg's result had been overlooked and the paper contained a sketch of an elementary proof of Theorem 3.2 taken from [23]. There is much overlap between the two approaches and we reproduce the essential ideas for the reader's benefit.

The first step follows the discounting arguments used in stochastic optimal control. Let $F \in \mathsf{Top}(n, n)$. Choose $0 < \alpha < 1$ and let $F_\alpha(x) = F(\alpha x)$. Then, by nonexpansiveness,

$$\|F_\alpha(x) - F_\alpha(y)\| \leq \alpha \|x - y\|\,,$$

which shows that F_α is a contraction. By the Banach Contraction Principle, [27, Theorem 2.1], F_α has a unique fixed point, $x_\alpha \in \mathsf{R}^n$, where $F_\alpha(x_\alpha) = x_\alpha$. In other words,

$$F(\alpha x_\alpha) = x_\alpha\,. \tag{11}$$

This procedure defines a function, $\alpha \to x_\alpha : (0, 1) \to \mathsf{R}^n$. The asymptotics of x_α as $\alpha \to 1$ from below (denoted $\alpha \to 1^-$) reveals a great deal about the cycle time vector. For instance, suppose that there are vectors $u_{-1}, u_0 \in \mathsf{R}^n$ such that, as $\alpha \to 1^-$,

$$x_\alpha = u_{-1}(1 - \alpha)^{-1} + u_0 + o(1)\,, \tag{12}$$

corresponding to a truncated Laurent series expansion about 1. The notation is intended to mean that the remainder term $x_\alpha - u_{-1}(1 - \alpha)^{-1} - u_0$ defines a function $g : (0, 1) \to \mathsf{R}^n$ such that $g(\alpha) \to 0$ as $\alpha \to 1^-$, [19]. Using (11) and nonexpansiveness, it is not difficult to show that

$$F(\alpha(1 - \alpha)^{-1}u_{-1} + u_0) = u_{-1}(1 - \alpha)^{-1} + u_0 + o(1)\,.$$

Suppose now that we take $\alpha = 1 - 1/k$ with $k \in \mathsf{N}$. As $k \to \infty$, $\alpha \to 1^{-1}$. Then

$$F(u_0 + (k - 1)u_{-1}) = u_0 + ku_{-1} + o(1) \tag{13}$$

from which it can be deduced by induction that $F^k(u_0) = u_0 + ku_{-1} + o(1)$. It follows that $\chi(F) = u_{-1}$, so that the residue of x_α—the coefficient of $(1-\alpha)^{-1}$—is the cycle time vector of F.

More can be said for functions in $\mathcal{A}^*$ because of their piecewise affine structure. If $F \in \mathcal{A}^*$ then any straight line, if extended far enough in R^n, must be mapped by F onto a straight line. This implies that the remainder term in (13) must vanish:

$$F(u_0 + (k - 1)u_{-1}) = u_0 + ku_{-1}\,,$$

for all sufficiently large k. It follows that there is some $K \in \mathsf{N}$ such that $u_0 + Ku_{-1}$ is a generalised fixed point of F.

The proof of Theorem 3.2 now reduces to showing that x_α has a truncated Laurent series expansion of the form shown in (12). Kohlberg's proof uses the same argument up to this point but then uses Farkas' Lemma to show that (12) holds. For Theorem 3.2, the hierarchical structure of $\mathcal{A}^*$ can be used instead. For functions in the class $(+, \mathsf{E})$, which are of the form $c + A$ where A is a row stochastic matrix, (12) follows from standard results in matrix theory. For functions formed by taking minima of maxima of these, the result follows from the fact that Laurent series like (12) are componentwise totally ordered under the lexicographic ordering on the pair (u_{-1}, u_0). Proposition 2.4 then does the rest. The full details of this argument appear in [23].

It is too much to expect that the fixed point theorem in Corollary 3.1 holds in general. Consider, for example, the nonnegative matrix

$$A = \begin{pmatrix} 1 & 1 \\ 0 & 1 \end{pmatrix} . \tag{14}$$

An easy calculation shows that $A^k(1,1)^{\mathsf{t}} = (k+1,1)^{\mathsf{t}}$. Hence, $\chi(\mathcal{E}(A)) = 0$. However, A does not have a positive eigenvector. To understand this phenomenon it is necessary to go beyond the cycle time vector. In the next section we discuss some ideas in this direction.

4 Lower order asymptotics

If $F \in \mathsf{Top}(n,n)$, the cycle time vector of F can be defined as the vector $\chi \in \mathsf{R}^n$ such that $F^k(x) = k\chi + o(k)$ as $k \to \infty$. As above, this notation is intended to mean that $(F^k(x) - k\chi)/k \to 0$ as $k \to \infty$, [19]. The argument of Lemma 3.1 was essential here to show that χ was well defined. The implication is that all trajectories are asymptotically linear, at least to order $o(k)$. It is not difficult to show that F can never grow faster than linearly. That is, given any $x \in \mathsf{R}^n$, $\exists A, B \in \mathsf{R}$, such that $kA \leq F^k(x) \leq kB$ for $1 \leq k$. What can be said about the growth of F^k at rates slower than k?

Consider functions $u : \mathsf{N} \to \mathsf{R}$ such that $u(k) \to \infty$ as $k \to \infty$. We call these rate functions. The inclusion function will be denoted by 1: $1(k) = k$. If $F \in \mathsf{Top}(n,n)$ and $x, y \in \mathsf{R}^n$, the nonexpansiveness property implies that, for any rate function, u,

$$F^k(x) - F^k(y) = o(u(k)) \ \text{ as } k \to \infty\,. \tag{15}$$

In other words, all trajectories are asymptotically equivalent, at all rates. If u and v are rate functions, the notation $u \succ v$ will indicate that $v(k)/u(k) \to 0$ as $k \to \infty$. This relation is clearly transitive: if $u \succ v$ and $v \succ w$ then $u \succ w$.

Definition 4.1 *A sequence of rate functions $(u_1, u_2, \cdots, u_m)$ is said to be an asymptotic scale if $u_1 \succ u_2 \succ \cdots \succ u_m$.*

Let $F \in \mathsf{Top}(n,n)$ and choose an asymptotic scale $(1, u_1, u_2, \cdots, u_m)$. Suppose that for points $x, y \in \mathsf{R}^n$ there are vectors $\tau_0, \tau^1, \cdots, \tau^m \in \mathsf{R}^n$ and $\theta^0, \theta^1, \cdots, \theta^m \in \mathsf{R}^n$ such that, as

$k \to \infty$,

$$\begin{array}{rcl} F^k(x) & = & k\tau^0 + u_1(k)\tau^1 + \cdots + u_m(k)\tau^m + o(u_m(k)) \\ F^k(y) & = & k\theta^0 + u_1(k)\theta^1 + \cdots + u_m(k)\theta^m + o(u_m(k))\,. \end{array} \tag{16}$$

Lemma 4.1 *Under the circumstances above, $\tau^i = \theta^i$ for $0 \leq i \leq m$ and $\tau^0 = \chi(F) = \theta^0$.*

Proof: Let $u_0 = 1$. It follows from the transitivity of $\succ$ that the equations in (16) continue to hold with i in place of m, for any $0 \leq i \leq m$. In particular, for $i = 0$, $F^k(x) = k\tau^0 + o(k)$ and $F^k(y) = k\theta^0 + o(k)$. It follows immediately from Lemma 3.1 that $\tau^0 = \chi(F) = \theta^0$. Furthermore, for any $0 \leq i \leq m$,

$$F^k(x) - F^k(y) = k(\tau^0 - \theta^0) + u_1(k)(\tau^1 - \theta^1) + \cdots + u_i(k)(\tau^i - \theta^i) + o(u_i(k))$$

Assume as an inductive hypothesis that $\tau^i = \theta^i$ for $0 \leq i < r$, where $0 < r \leq m$. Using (15), we see that $u_r(k)(\tau^r - \theta^r) = o(u_r(k))$. Hence, $\tau^r = \theta^r$ and the result follows by induction.

We shall say that F has cycle times with respect to the asymptotic scale $(1, u_1, \cdots, u_m)$ if an equation of the form in (16) holds. In this case the notation $\chi(F, u_i)$ will denote the corresponding vector τ^i, which we have just shown to be uniquely determined by F and the chosen asymptotic scale. The cycle time vector of Definition 3.1 corresponds to $\chi(F, 1)$. This notation is potentially misleading since the value of $\chi(F, u_i)$ depends on the chosen scale as well as on the specific rate function u_i. The scale should be clear from the context and we prefer to keep the notation lightweight.

The point of this additional complexity is that if F has a fixed point, so that $F(x) = x + h$, then $F^k(x) = kh + o(u(k))$ for any rate function u. Hence, by Lemma 4.1, F has cycle times for any asymptotic scale, $(1, u_1, \cdots, u_m)$, and, furthermore, $\chi(F, 1) = h$ and $\chi(F, u_i) = 0$ for all $1 \leq i \leq m$. This is a much stronger condition than just requiring $\chi(F, 1) = h$. It suggests the form that a generalised fixed point theorem could take.

Conjecture 4.1 *Let $C \subseteq \mathsf{Top}(n, n)$ be a subset of topical functions, such as the subset of nonnegative matrices. Does there exist an asymptotic scale $(1, u_1, \cdots, u_m)$ such that every $F \in C$ has cycle times with respect to this scale and, furthermore, that $F \in C$ has a fixed point if, and only if, $\chi(F, 1) = h$ for some $h \in \mathsf{R}$ and $\chi(F, u_i) = 0$ for $1 \leq i \leq m$?*

This paragraph is perhaps less a conjecture than a suggestion as to the form that an answer might take. There is no *a priori* reason why scales should not be infinite or even continuous, as in the scale $(k^{1/a})$ where $1 \leq a \in \mathsf{R}^+$, but we have not allowed for this. We have allowed for the possibility that there is no single asymptotic scale that works for all topical functions. Theorem 3.1 suggests that this unlikely to be the case. Let $(1, u_1, \cdots, u_m)$ be any asymptotic scale such that for each $1 \leq i \leq m$, there exists $0 \leq M_i \in \mathsf{R}$ such that $u_i(k) - u_i(k-1) \in [0, M_i]$. Note that this condition is satisfied by familiar rate functions like k^a (for $a \leq 1$) and $\log(k)$. It is easy to see, using Theorem 3.1, that there is a topical function which has cycle times for this asymptotic scale. Of course, the mere existence of an asymptotic scale does not imply the fixed point conclusion of Conjecture 4.1. A given function may have cycle times with respect to many different scales. The crux of the Conjecture is the existence of a scale from which the existence of fixed points can be deduced.

What evidence is there for this? Theorem 3.2 can be reinterpreted as saying that the scale (1) works for the class $\mathcal{A}^*$. The functions with affine structure require only the linear growth rate. More interestingly, two old results in the literature on nonnegative matrices can also be reinterpreted in this language and show that the conjecture does explain the fixed point behaviour of examples like (14).

First, Rothblum and Whittle investigated growth rates for Markov decision processes in [53]. We claim that their results can be reinterpreted as follows.

Theorem 4.1 *If A is a $n \times n$ nonnegative matrix satisfying (8) then $\mathcal{E}(A)$ has cycle times with respect to the asymptotic scale* $(1, \log)$.

In other words, as $k \to \infty$,

$$\mathcal{E}(A^k)(x) = k\chi(\mathcal{E}(A)) + \log(k)\chi(\mathcal{E}(A), \log) + o(\log(k)) .$$

$\chi(\mathcal{E}(A))$ and $\chi(\mathcal{E}(A), \log)$ correspond to the geometric and algebraic growth rates, respectively, of [53].

Second, an old result, going back to Gantmacher in the 1950s, gives a necessary and sufficient condition for a nonnegative matrix to have a positive eigenvector, [5, Chapter 2, Theorem 3.10]. We claim that this can be reinterpreted as follows.

Theorem 4.2 *If A is a nonnegative matrix satisfying (8) then A has a positive eigenvector corresponding to its spectral radius r if, and only if, $\chi(\mathcal{E}(A)) = r$ and $\chi(\mathcal{E}(A), \log) = 0$.*

Proofs of these assertions will appear in due course. It is insightful to work out the 2×2 case, where the calculations can be easily done. Let $\{a, b, c\} \subseteq \mathsf{R}^+$. Consider the nonnegative matrix

$$B = \begin{pmatrix} a & b \\ 0 & c \end{pmatrix} .$$

(The other cases in dimension 2 are either trivial or uninteresting.) We can work out the eigenvector problem in 3 different ways. A simple calculation with the eigenvalue equation $B(x, y)^{\mathsf{t}} = \lambda(x, y)^{\mathsf{t}}$ shows that B has a positive eigenvector if, and only if, $c > a$.

In the language of [5, Chapter 2, §3], B has two strongly connected components (classes) corresponding to the vertices 1 and 2 and $\{2\}$ is the unique final class. The spectral radius of B is $c \vee a$. A class is basic if the spectral radius of the corresponding irreducible submatrix equals the spectral radius of B. [5, Chapter 2, Theorem 3.10] states that B has a positive eigenvector if, and only if, the basic classes coincide with the final classes. There are hence 3 possibilities

Condition	Final classes	Basic classes
$c > a$	$\{2\}$	$\{2\}$
$c = a$	$\{2\}$	$\{1\}, \{2\}$
$c < a$	$\{2\}$	$\{1\}$

(17)

of which only the first gives a positive eigenvector.

The asymptotics of the trajectories of B can be calculated as follows. Write

$$B^k = \left(\begin{array}{cc} a^k & r_k \\ 0 & c^k \end{array} \right),$$

where $r_k = a^{k-1}b + r_{k-1}c$. It follows that $r_k/a^k = b/a + (r_{k-1}/a^{k-1})(c/a)$ and hence

$$r_k = \left\{ \begin{array}{ll} a^k \left(\frac{b}{a}\right) \left(\frac{1-(c/a)^k}{1-(c/a)}\right) & \text{if } a \neq c \\ a^k \left(\frac{b}{a}\right) k & \text{if } a = c \end{array} \right. .$$

It is now easy to check that $\mathcal{E}(B)$ has cycle times with respect to the asymptotic scale $(1, \log)$ and that their values are as follows.

$$\begin{array}{ccc} \text{Condition} & \chi(\mathcal{E}(B)) & \chi(\mathcal{E}(B), \log) \\ c > a & (\log(c), \log(c))^{\mathsf{t}} & (0,0)^{\mathsf{t}} \\ c = a & (\log(c), \log(c))^{\mathsf{t}} & (1,0)^{\mathsf{t}} \\ c < a & (\log(a), \log(c))^{\mathsf{t}} & (0,0)^{\mathsf{t}} \end{array} \tag{18}$$

According to Theorem 4.2, $\mathcal{E}(B)$ has a fixed point if, and only if, $c > a$. Comparing (18) with (17) gives some insight into the workings of Theorems 4.1 and 4.2.

We can answer positively the question raised in Conjecture 4.1, at least for the subset of nonnegative matrices. As one final piece of evidence, consider a topical function $F : \mathsf{R}^n \to \mathsf{R}^n$ for which there is some $h \in \mathsf{R}$ such that $F^k(x) - kh$ is bounded as $k \to \infty$. In other words, $F^k(x) = kh + O(1)$, in the usual notation, [19]. In this case, F clearly satisfies the conclusions of Conjecture 4.1 for any asymptotic scale. We should therefore expect it to have a fixed point.

To see that it does, let $G = F - h$. By assumption, there is $M \in \mathsf{R}$ such that $\|G^k(x)\| \leq M$ for all $k \in \mathsf{N}$. Consequently we can define $u, v \in \mathsf{R}^n$ by

$$u = \lim_{k\to\infty} \bigvee_{k \leq m} G^m(x) \qquad \text{and} \qquad v = \lim_{k\to\infty} \bigwedge_{k \leq m} G^m(x)\,,$$

where the limits in question exist because the sequences concerned are, respectively, monotone decreasing and monotone increasing. Since G is continuous, it follows easily from the monotonicity property that $u \leq G(u)$ and $G(v) \leq v$. Hence $G^k(u)$ is a monotone increasing sequence and $G^k(v)$ a monotone decreasing sequence. Both most converge since, by nonexpansiveness, $\|G^k(u) - G^k(v)\| \leq \|u - v\|$. If $G^k(u) \to u^*$, then clearly $G(u^*) = u^*$ and so $F(u^*) = u^* + h$, as required. Conversely, if F has a fixed point, where $F(x) = x + h$, then clearly $F^k(x) - kh = x$ for all $k \in \mathsf{N}$.

Lemma 4.2 *Let $F \in \mathsf{Top}(n, n)$. F has a fixed point if, and only if, there exists $h \in \mathsf{R}$ and $x \in \mathsf{R}^n$ such that $F^k(x) - kh$ is bounded as $k \to \infty$.*

(This result is quite useful. It shows, for instance, that if F has a periodic point, where $F^p(x) = x + h$ for some $p \in \mathsf{N}$, then it must have a fixed point.)

These different observations give some encouragement that the ideas of asymptotic scales and cycle times are the right ones for formulating a general fixed point theorem for topical functions. An entirely different approach to the fixed point problem, generalising the classical Perron-Frobenius theorem, may be found in [25].

5 Summary

Engineers who build discrete event systems have to confront dynamical problems as a matter of course. For the most part, they have had little mathematical support to do this, despite the considerable understanding of dynamical systems arising from classical mechanics and the study of chaos. As we have seen in this paper, discrete event systems give rise to very different issues. They can lead naturally to dynamics which are nonexpansive in the ℓ^∞ norm. Nonexpansiveness constrains the dynamical behaviour and forces all trajectories to have the same asymptotics. It is this fundamental observation that allows performance measures like the cycle time vector to be defined.

What is interesting and unexpected is the close relationship that has emerged between cycle times and fixed points. This would not have been expected from the linear examples and there is little hint of it in Perron-Frobenius theory. The results surveyed in this paper show that the existence of fixed points can be deduced from the asymptotics of trajectories; a new dynamical insight into an old classical problem.

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