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The text serves as a supplement to existing books on structured linear algebra problems, rational approximation and orthogonal polynomials. Features of this book: • provides a unifying approach to linear algebra, rational approximation and orthogonal polynomials.

Parte 1 de 6 Preface It is very interesting to see how the same principles and techniques are developed in different fields of mathematics, quite independently from each other. It is only after a certain maturity is reached that a result is recognized as a variation on an old theme. This is not always a complete waste of effort because each approach has its own merits and usually adds something new to the existing theory. It is virtually impossible and there is no urgent need to stop this natural development of things. If tomorrow a new application area is emerging with its own terminology and ways of thinking, it is not impossible that an existing method is rediscovered and only later recognized as such. It will be the twist in the formulation, the slightly different objectives, an extra constraint etc. The availability of new technological or mathematical tools will force researchers to rethink theories that have long been considered as complete and dead as far as research is concerned. In this text we give a good illustration of such an evolution. For the underlying principle we have chosen the algorithm of Euclid. It is probably the oldest known nontrivial algorithm, which can be found in the most elementary algebra textbooks. It is certainly since the introduction of digital computers and the associated algorithmic way of thinking that it received a new impetus by its many applications which resulted in an increasing interest, but its simplicity in dealing with situations that are, at least in certain problem formulations not completely trivial, explains its success. Already in ancient times, long before modern computers became an essential part of the scene, the algorithm has been used in many applications. In its original form, it deals with a geometrical problem. At least, Euclid himself describes it in his 7th book of the Elements as a way of constructing the largest possible unit rule which measures the length of two given rules as an integer times this unit rule. Nowadays we recognize the Euclidean algorithm as a method to compute the greatest common divisor of two integers or of two polynomials. Of course, the distinction between different mathematical disciplines is purely artificial and is invented by mathematicians. Luckily, the self-regulating mathematical system maintains such links between the different types of mathematicians, and prevents them from drifting too far apart. It was recognized with the invention of continued fractions that the algorithm does not only compute the final result: The next, quite natural step, is to apply the algorithm to test whether a number is rational or not and to see what happens when the number is not rational. The algorithm will go on indefinitely, and we get an infinite continued fraction expansion. The study of these expansions became a useful and powerful tool in number theory. The same technique can be applied to infinite formal power series, rather than just polynomials, and again the algorithm will end after a finite number of steps if we started from a representation of a rational fraction or it will give an infinite formal expansion which might or might not converge in a certain region ϵ . This hooks up the Euclidean algorithm with rational approximation theory. From an algebraic point of view, the Euclidean domains and several of its generalizations became a study object in their own right. From the approximation side, the kind of rational approximants that you get are known as Padé approximants. Although this theory has celebrated its hundredth anniversary, the recognition of the Euclidean algorithm as an elegant way of constructing approximants in a nonnormal table came only a couple of decades ago. Traditionally, the computation of a Padé approximant was done via the solution of a linear system of equations. The matrix of the system has a special structure because it contains only $O(n)$ different elements while the entries on an antidiagonal are all the same. It is a Hankel matrix. The linear algebra community became interested in solving this special type of systems because their solution can be obtained with sequential computations in $O(n^2)$ operations, rather than the $O(n^3)$ for general systems. The Hankel matrices, and the related Toeplitz matrices, show up in numerous applications and have been studied for a long time and that explains why it is important to have efficient

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solution methods for such systems which fully exploit their special structure. Not only the solution of such systems, but also other, related linear algebra problems can benefit from the known theory of the Euclidean algorithm. The Lanczos algorithm, which is recently rediscovered as a fashionable research area is intimately related to the Euclidean algorithm. Again the algorithm of Euclid can serve as an introduction to the fast growing literature on fast algorithms for matrices with special structure, of which Toeplitz and Hankel matrices are only the most elementary examples. Given the moments for some inner product, the problem is to find the orthogonal polynomials and eventually the measure itself. To have a genuine inner product, the moment matrices should be positive definite and strongly nonsingular, that is, all its principal leading minors are nonsingular. The analogs of the Euclidean algorithm which can handle these singular situations are generalizations of the Schur and Szegő recursions in classical moment theory. A final cornerstone of this text that we want to mention here is linear systems theory. This is an example of an engineering application where many, sometimes deep, mathematical results come to life. Here, both mathematicians and engineers are active to the benefit of both. The discipline is relatively young. It was only since the thirties that systems theory became a mathematical research area. In the current context we should mention the minimal partial realization problem for linear systems. The minimality of the realization is however important from a practical point of view. The latter was originally developed as a method for handling error-correcting codes by shift register synthesis. It became known to the engineering community as also solving the minimal partial realization problem. Another aspect that makes systems theory interesting in this aspect is that in this area it is quite natural to consider systems with n inputs and m outputs. When m and n are equal to 1, we get the scalar theory, but with m and n larger than 1, the moments, which are called Markov parameters in this context, are matrices and the denominators of the realizations are square polynomial matrices and the numerators rectangular polynomial matrices. So, many, but not all, of the previously mentioned aspects are generalized to the matrix or block matrix case for multi-input multi-output systems. The translation of results from multi-input multi-output systems theory to the fields mentioned above was one of the main incentives for putting the present text together. In this book we shall only consider the scalar theory and connections that we have sketched above. Excellent textbooks exist on each of the mentioned areas. In most of them the Euclidean algorithm is implicitly or explicitly mentioned, but the intimate interplay between the different fields is only partially covered. It is certainly not our intention to replace any of these existing books, but we want in the first place put their interconnection at the first plan and in this way we hope to fill an empty space. We make the text as selfcontained as possible but it is impossible to repeat the whole theory. If you are familiar with some of the fields discussed it will certainly help in understanding our message. And much more on formal orthogonal polynomials is given in A. First we guide the reader from the simplest formulation of the Euclidean algorithm to a more abstract formulation in a Euclidean domain. We give some of its variants and some of its most straightforward applications. In a second chapter we discuss some aspects and applications in linear algebra, mainly including the factorization of Hankel matrices. In the third chapter, we give an introduction to the Lanczos algorithm for unsymmetric matrices and some of its variants. The fourth chapter on orthogonal polynomials translates the previous results to orthogonal polynomials with respect to a general biorthogonal form with an arbitrary moment matrix. The Hankel matrices that were studied in previous chapters are a very special case. We also give some results about Toeplitz matrices which form another important subclass. This is not really essential, but it forces us to be careful in writing the products and inverses so that the results reflect already at least partially the block case. The next chapter gives a short introduction to linear systems and illustrates how the previous results can be used in this context. It includes a survey of recent developments in stability tests of R . Finally, Chapters 7 and 8 give some less elaborated perspectives of further applications which are closely related to what has been presented in the foregoing chapters. It also introduces the look-ahead strategy for solving such problems and which is most important in numerical computations. It is left to the imagination of the reader to translate the look-ahead ideas to all the other interpretations one can give to these algorithms in terms of rational approximation, of orthogonal

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polynomials, iterative methods for large matrices, x PRE, FACE solution of structured systems etc. The last chapter introduces the application of the Euclidean algorithm in the set of Laurent polynomials to the factorization of a polyphase matrix into a product of elementary continued fraction-like matrices. These polyphase matrices occur in the formulation of wavelet transforms and the factorization is interpreted as primal and dual lifting steps which allow for an efficient computation of wavelet transform and its inverse. While we were preparing this manuscript, we became aware of the Ph.D. thesis by P. P. V. That is Rational approximation, Orthogonal functions, Linear algebra, Linear systems, and Signal processing. The remarkable observation is that the Euclidean algorithm, in one form or another, is a "greatest common divisor" of all these topics.

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The text serves as a supplement to existing books on structured linear algebra problems, rational approximation and orthogonal polynomials. Features of this book: provides a unifying approach to linear algebra, rational approximation and orthogonal polynomials; requires an elementary knowledge of calculus and linear algebra yet introduces.

Chapter 1 Euclidean fugues 1. It is best known as an algorithm to compute a greatest common divisor of two integers or two polynomials, but it can as well be used to compute a greatest common divisor of two elements from a general Euclidean domain. This is commonly defined as an integral domain where a certain division property holds which forms the basis of the Euclidean algorithm. For example, consider the set of integers \mathbb{Z} and let us denote the absolute value of a $E \in \mathbb{Z}$ by $|a|$. For the set of positive integers, one could simply describe the Euclidean algorithm as follows: Given a couple of positive integers, we subtract the smallest number from the larger one and replace the largest one by this difference. We do the same with the resulting couple until the numbers are equal. Then we have found a greatest common divisor of the given couple. The successive subtractions simulate the divisions. Note that relation 1. We could write e . Both of these satisfy the property 1. There is a remedy for this nonuniqueness, which we shall give in section 1. The main step of the algorithm is an application of the division property. We compute r_k as a remainder when r_{k-2} is divided by r_{k-1} . As a matter of fact, because of this nonuniqueness, the greatest common divisor will not be unique either, and strictly speaking, we should refer to a greatest common divisor. It turns out however, and we come back to this in the next section, that whatever the choice made at every step of the Euclidean algorithm, one will always end up with the same greatest common divisor up to a sign change. Note also that the algorithm will certainly terminate since $|r_k|$ is a strictly decreasing sequence of nonnegative numbers. Hence r_k will eventually become zero. However some of the entities have to be reinterpreted. The absolute value of the integers should be replaced by the degree of the polynomial. This explains why we introduced the curious 1. For the polynomial case, there is no freedom in the choice of the quotient and the remainder in every step, but as will be seen in section 1. In elementary textbooks on algebra, one finds the notion of a Euclidean domain, which is an integral domain with a function v . This function has exactly the same properties for the elements of the general Euclidean domain as the absolute value function had for the elements of the Euclidean domain \mathbb{Z} . Thus in the general Euclidean domain, a division property like 1. In view of a possible generalization, we briefly review the theory of greatest common divisors in Euclidean rings. A Euclidean ring is a slight generalization of a Euclidean domain in the sense that it need not be commutative. We consider an integral ring R which is a ring without zero-divisors. This means the following: The inverse of an element need not exist, but all the elements that do have an inverse, form a multiplicative group. The invertible elements are called units. Note that the latter two properties imply the cancellation law: This in turn implies that a left inverse is also a right inverse. If the monoid is a commutative multiplicative structure, then the integral ring is called an integral domain. A skew field is sometimes called a division ring. Thus, besides the other properties, the main differences are in the properties of the multiplicative group R^\times as given in the following table

R^\times	Do
group	not Abelian
integral ring	skew field
Abelian	commutative field
integral domain	Unless stated otherwise, we shall assume in this chapter that R represents an arbitrary integral ring. For a field we shall use the notation F . Since in general we do not have commutativity, we should add to most of the notions the prefix left or right. We develop the theory mainly for the left versions and assume the reader can construct the right duals for him or herself. Of course for an integral domain or a commutative field, the distinction between left and right disappears. We now introduce some notions from divisibility theory. Note that any element from R will be a left divisor of 0. Thus we can write $a 0$, $\forall a \in R$. On the other hand 0 is a left divisor of 0 but of nothing else: The following properties are elementary to prove and can be found in any elementary textbook on algebra. We shall not repeat the proofs here. Note that the equivalence class of 0 contains only one element: The third statement in the previous theorem says that the left divisibility property of two elements

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propagates to all their left associates in the same equivalence class. Thus it suffices to study divisibility in the quotient structure of equivalence classes, i . It is then most convenient to choose a uniquely defined representative for each of the equivalence classes. For the other equivalence classes one agrees upon a particular choice. Common practice is to represent a nonzero equivalence class in Z by its positive representative. A greatest common left divisor g . Note that if one of the elements is zero, then the other element will always be a g . This might be surprising but it is conform to the previous definition. Because both g and h are g . For practical computations however, one can temporarily disregard the uniqueness and use some normalizations that turn out to be convenient at that moment. If one ends up with some representative of the equivalence class of g . For further reference, we give one more definition of prime and coprime elements, before we pass to the definition of Euclidean ring and the Euclidean algorithm. Otherwise we call p composite. It should be stressed that in an arbitrary integral ring, there need not exist a g . Hence it can not be decided which one is the "greatest". However if the integral ring possesses some extra property which turns it into a Euclidean ring, then there will always be a g . Note the switch that we make here. We shall use the right sided Euclidean algorithm in a right sided Euclidean ring to compute a greatest common left divisor. So now we come to the definition of a right sided Euclidean ring. Recall that we denote the nonzero elements of: If 1 is an integral domain, then this defines a Euclidean domain. This is not the classical definition. Usually, one imposes that 1 is a ring without zero-divisors which need not have a unit-element a priori but in 1 . As before, we shall denote the above decomposition of a by div and mod operations but, to make the left and right difference, we denote the q and r obtained by the relations above as $q\text{-aldiv}b$ and $r\text{-almod}b$. Note that more choices for 0 - are possible. The cases where at least one of s or r is zero are trivial to verify. So we shall suppose that none of them is zero. In general the existence of a g . Hence the set of common left divisors for the couple a, b is the same as for the couple $b, \text{almod}b$. The sequence thus generated must end after a finite number of steps because $0 \leq r_k$ is a strictly decreasing sequence of nonnegative integers. This means that r_{n-1} is a left divisor of r_n . We also know that all common left divisors of r and s are also common left divisors of r_{n-1} and r_n Parte 2 de 6.

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