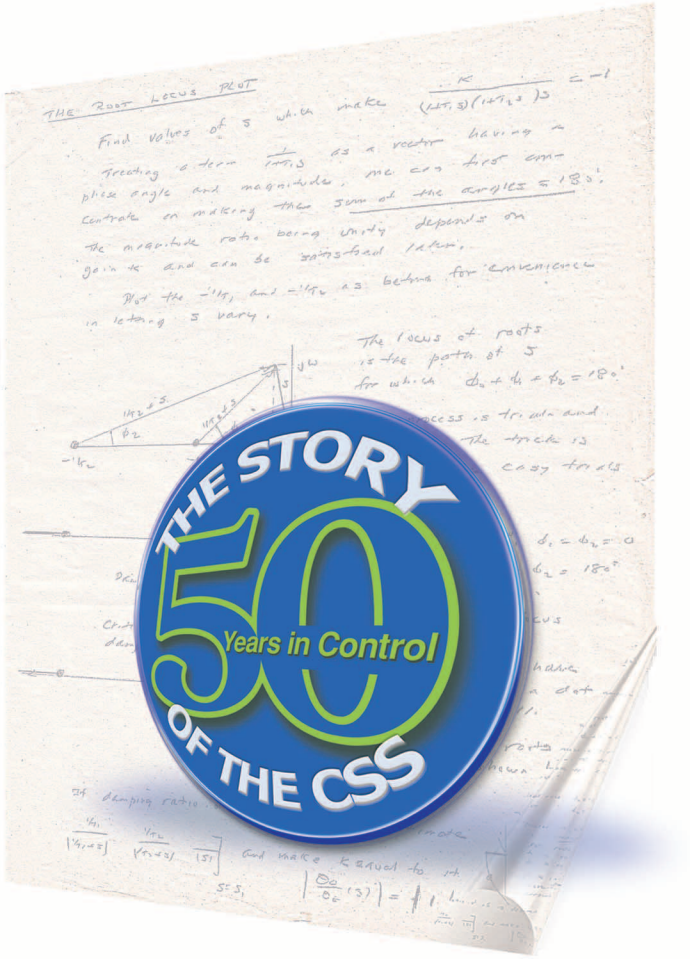
FEATURE

Bringing Root Locus to The Classroom



The story of Walter R. Evans and his textbook *Control-System Dynamics*

by Gregory Walter Evans

Fifty years ago, on 30 September 1954, the McGraw-Hill Company published *Control-System Dynamics* by Walter R. Evans as the 40th entry in its popular "Electrical and Electronic Engineering Series." Six years earlier Evans had helped usher in a revolution in the practice of servomechanism design with his root-locus method. Engineers trained in its use were able to shape the dynamic responses of their servo designs starting from the poles and zeroes of their characteristic equations. Engineering educators would need a new textbook to describe the method to their students. With *Control-System Dynamics*, Evans sought to satisfy that need with a book emphasizing the physical picture over mathematical formalisms. Its development took him on a journey over a road less traveled.

1941–1948: Lamentations and Foundations

In 1948 John Wiley and Sons published a book destined to become a classic: *Principles of Servomechanisms* by Gordon Brown and Don Campbell of MIT. The authors acknowledged the importance of the characteristic equation's roots but lamented the obstacles confronting all known algebraic methods of solving for them, writing "Therefore, with the exception of being able to treat the most elementary forms, the whole structure of algebraic synthesis is of very small value" [1].

Brown and Campbell referred readers who were interested in learning rules for calculating the roots of characteristic equations to the book *Mathematics of Modern Engineering*. Its authors, Robert Doherty and Ernest Keller, had developed it for courses they taught at the General Electric Company's "Advanced Course," a program Doherty founded in 1922. Ironically, in their "Forward for Instructors," the book's authors lamented the practice of teaching mathematical rules rather than mathematical reasoning, writing that

> The use of mathematics as a tool in straight thinking is, in the authors' opinion, not at all what it should be. . . . Merely to remember some formula and the type of problem to which [the results of others] are applicable is of little avail in solving a new, practical problem. For the latter, not only is a knowledge of the basic engineering sciences necessary, but also a mind disciplined in sound reasoning. [2]

Having defined the problem, the authors offered their recommended solution:

> Often the clearest approach to a mathematical concept, function, or theory is through the solution of an introductory problem, rather than through a formal approach by means of definitions, axioms, and theorems. . . . An engineer is interested primarily in the application of mathematics to the solution of problems. [2]

Evans was a product of Robert Doherty's philosophy, both taking and teaching classes in the Advanced Course from 1941 to 1946. (See Figure 1.) There he mastered methods for attacking problems using principles rather than

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Figure 1. *Walter R. Evans as a student in the 1940s. Evans was a life-long student and teacher. He credited his own approach to problem solving to his teachers "for their emphasis on understanding rather than superficial knowledge." He cited the specific inspiration for the root-locus method to a question asked by an unknown student in his class at North American Aviation, "How large can the second time delay in a system be compared to the first one before the rules for a quadratic to be too much in error?"*

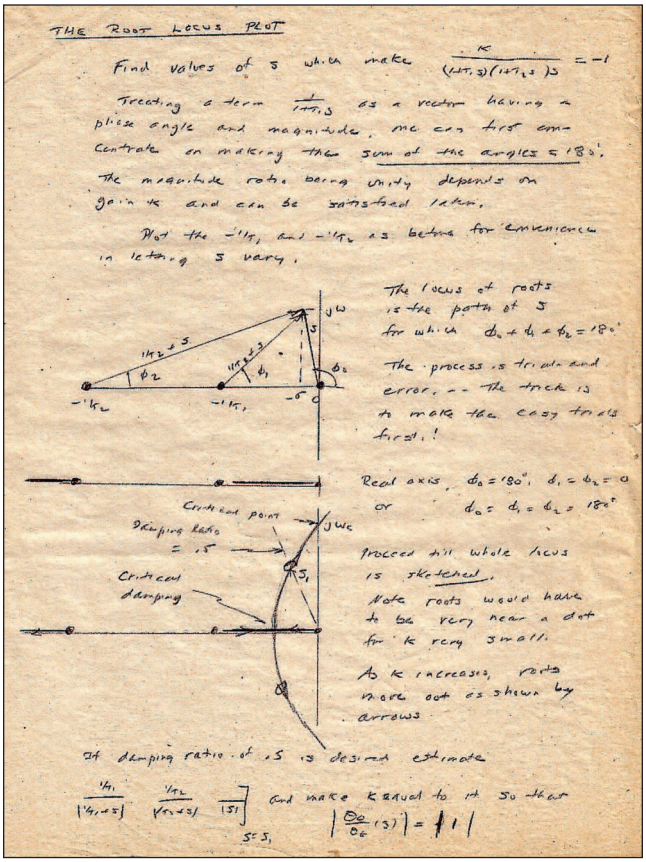

Figure 2. *The root-locus idea. "I've long thought it would be a sporting idea to write up the root-locus idea the way I came to understand it," Evans wrote in a four-page, June 1949 letter to Orrin Livingston, a friend at General Electric. On the last page, shown here, Evans showed how the characteristic equation could be solved by plotting the locus of points "s" that have a simple relationship with other known points, that is, angles that sum to 180°. Evans developed a simple, sequential process, which engineers used to generate sketches in seconds, and a specialized protractor, which supported high accuracy in minutes. First used by North American Aviation designers and taught at UCLA, the application and instruction of Evans' new method spread rapidly to other companies and universities.*

memorized rules, for using graphical plots to visualize mathematical equations, and for starting with simple cases and building up to more complex ones. The foundations of Evans' root-locus method (see Figure 2) and its presentation in *Control-System Dynamics* are traceable directly to lessons learned in General Electric's Advanced Course.

1949: A Memorandum of Agreement with McGraw-Hill

In 1949 McGraw-Hill's distinguished "Electrical and Electronic Engineering Series" had no entry in the rapidly developing field of servomechanisms. The publisher turned to electrical engineering Prof. R.J.W. Koopman of Washington University in St. Louis about the possibility of his preparing a textbook on the subject. Shortly thereafter, however, Koopman succeeded Roy Glasgow as department chairman, and progress on a manuscript slowed dramatically. Koopman suggested to McGraw-Hill that they ask a former Washington University instructor, Walter R. Evans, then at the Aero Physics Laboratory of North American Aviation, whether he would be interested in writing a book using course notes developed at Washington University, Emerson Electric, and North American Aviation. On 2 August 1949, editor John Wight wrote Evans:

> We have nothing in the way of an immediate prospect which could be considered competitive with the distinguished book by Brown and Campbell. I gather your work . . . would include material both below and above the academic pitch of Brown and Campbell. . . . I know that Dean Terman will be most pleased to have an opportunity to look your material over.

The consulting editor of the series, Frederick Emmons Terman, had helped launch the series with his 1937 book *Radio Engineering*. By 1949 Terman had assured his place in history as the "father of Silicon Valley" through his encouragement of students, including Bill Hewlett and David Packard, to start

new companies adjacent to Stanford University to create job opportunities for graduating students.

On 21 August 1949 Evans accepted McGraw-Hill's invitation and, in a letter to editor Wight, included a warning of the unconventional approach he planned to take:

> The main purpose of the book is to demonstrate the root locus method. . . . If the book could be made as competitive as the method itself, I am sure that you as publisher and I as author would be most pleased. Frankly, there is a gamble involved for each of us in that books emphasizing the physical picture of a subject are in the minority compared to those in which the mathematics dominates. I am personally convinced from teaching General Electric's Advanced Engineering Courses and undergraduate courses at Washington University, however, that the students themselves want the physical picture.

Both the author and the publisher sought an early completion date. Editor John Wight expressed McGraw-Hill's business goals in an October 1949 letter to Evans.

> The Servomechanisms market is growing with great rapidity. There are, as you know, good books already on the market and certainly more will be written. For this reason, we are most anxious to get your book underway and hope you will find the time to finish the manuscript at a reasonably early date.

On 1 November 1949 Evans signed and mailed a memorandum of agreement with McGraw-Hill Publishers for a book to be titled *Control-System Dynamics*.

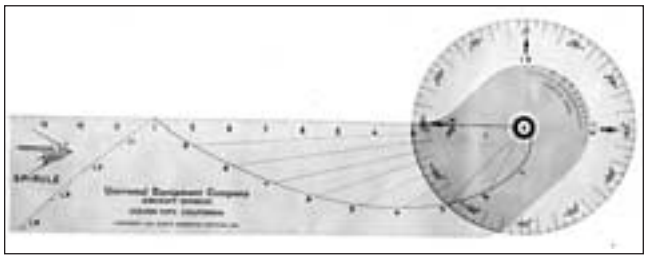

Figure 3. *The Spirule. The Spirule consists of an arm and a disk held together by an eyelet that also serves as a pivot point. On a root-locus plot, the pivot point is placed at a trial point, and the arm is rotated with respect to the disk through each of the vector angles to obtain their sum. In 1952 Evans formed the Spirule Company and, over the course of 30 years, shipped more than 100,000 units to students and engineers in every state and 75 countries. In 1956 an unknown UCLA engineering student expressed his feelings in verse, "You do 16 tons, and what do you learn? Slide rule's busted, and the Spirule won't turn. Saint Peter, don't you call me, there's too much fuss, I owe my soul to the root locus."*

1950: A Promising Beginning

Walter Evans celebrated his 30th birthday on 15 January 1950 by writing John Wight a letter suggesting they meet while Evans was in New York to deliver his seminal paper "Control System Synthesis by the Root Locus Method" [3] at the AIEE Winter Meeting. When Evans met Wight, he estimated he would have a first draft complete by 1 June. He committed himself to the project by setting up an office in a spare bedroom of a neighbor across the street. From his home each morning, after he told his children he was leaving with his carpool for work, he simply walked across Maple Street to work on the book. By mid-June Evans had completed a first draft and began his own process of revision, receiving suggestions for improvements from colleagues at North American.

In December, he submitted manuscript samples to McGraw-Hill and committed to having it completed by 1 March 1951. He estimated the final text in published form would be 170 pages but expected its 488 figures would raise the total count to between 300 and 350 pages. Evans wanted his book to be affordable and expressed the "hope that such a book can still sell for about $5.00." Ken Ziegler, who had taken over editorial responsibilities from John Wight, responded within a week. "We are delighted to hear that you have made such good progress on the manuscript and hope that our Editing Department will be able to handle it in its present form."

1951: Competition, Controversy, and the Spirule

Soon after publication of Evans' 1950 paper, a root-locus-inspired revolution in servomechanism design spread across the country. Students and aspiring authors wrote Evans of their interest in it. An MIT graduate student named John G. Truxal wrote his 1950 Ph.D. thesis on the subject "Servomechanism Synthesis Through Pole-Zero Configurations" [4]. In 1951, by then an assistant professor at Purdue, Truxal wrote Evans:

> I was quite pleased to hear while at the IRE Convention in New York of the wide acceptance your ideas seem to be gaining—particularly the underlying philosophy of controlling both the transient and frequency response through control of pole and zero positions. I believe people are slowly beginning to realize that the necessity in so many problems of control . . . practically screams for a synthesis with some concern over the actual positions of the relevant poles and zeros.

Aspiring authors of servomechanism books wrote Evans asking his permission to include the root-locus method in their texts. Among them were Floyd Nixon [5] and George Thaler [6]. Evans gave his consent without reservation, and yet these inquiries caused him concern for the fate of his manuscript. In March 1951, in a letter to

Ziegler, Evans wrote, "I would like to know what other books are in preparation and an estimate of the probable date of publication of my text compared to the others."

At the same time as he had this concern, Evans was pursuing a related project, the production of a plastic protractor called a "Spirule," shown in Figure 3, that enabled users to make accurate root-locus plots quickly. If McGraw-Hill bundled a Spirule with his book, he thought, they could differentiate his book in the market place and save its buyers the trouble of making a separate Spirule purchase. Once before he had discussed this idea with John Wight. With competition looming, he raised it again with Ken Ziegler. As always, the impact on cost was a key issue.

> This device is used on root locus plots to obtain accurate measurements rapidly. The basic cost is 40 cents each in quantity production. On the basis of these facts I would like to know your opinion of the sales value of having the device enclosed. . .

The following week, Ziegler advised against enclosure of a Spirule, writing, "It would definitely add to the expense (and, therefore, the list price of the book) and I doubt very much that it would increase the sales potential of the book." He also informed Evans of several servomechanism books in preparation, namely, Ahrendt and Taplin [7], Chestnut and Mayer [8], and Thaler and Brown [6], with the first due for publication within six months.

In the spring of 1951, Evans completed the remainder of the manuscript and modified notation and equations to conform to standards that McGraw-Hill's editorial department had provided him. In a letter expressing his disagreement with Zeigler's recommendation against enclosure of a Spirule, he wrote, "Most of the engineers back here at North American Aviation believe that it should be enclosed, and some have suggested that the reader might resent having to make a separate purchase."

In the autumn of 1951, two years after entering into their memorandum of agreement, McGraw-Hill informed Evans that, based on the report of their technical advisor, the manuscript would require reworking, including the introduction of problem sets. Interestingly, the technical reviewer expressed his support for including a Spirule with the book, writing "The instrument called the "Spirule" should probably be included with the text since its use is treated rather fully . . ."

In addition to his recommendation that Evans add problems and include a Spirule, the reviewer questioned Evans' avoidance of the Laplace transform in his introduction of transfer functions. On this point, Evans would not budge. He had consciously departed from standard practice because it had been his experience that students substituted rote learning of the rules of use for a physical understanding of the problem at hand. Consulting Editor Terman tactfully agreed with the reviewer, writing "the suggestion that the Laplace transform might be used is one that the author should consider seriously."

Evans helped usher in a revolution in the practice of servomechanism design with his root-locus method.

In the following week, Evans prepared a defense of his case in an essay he called *An Opinion Concerning the Laplace Transform*. Although it is the most passionate discussion Evans ever wrote about the education process, he had second thoughts about its sharp tone and wired Zeigler to destroy it rather than deliver it to Dean Terman. He kept a copy for himself. In retrospect, its candor contributed to its persuasive power:

> The Laplace transform is admittedly the simplest way to present many conclusions regarding transform functions; I do not believe however that it is the simplest way for the student to understand them. Of course many students do not seek understanding; show them a routine, assign a few problems for practice, give them a straightforward exam, and if they pass it, they leave the course feeling educated. If however some of the problems are not essentially duplicates of the homework problems, they fail miserably and then complain of the examination as being "unfair." The fault does not lie entirely with the students and not with the Laplace transform itself, but I do not believe that the above method of education should be encouraged. The graduate of such a system is of little more value to industry with the course than without it. If he has to solve a problem, he must take time to reestablish the routine. If he makes an algebraic error, he may arrive at a ridiculous result without recognizing it. . . . Admittedly there is no foolproof way of presenting a method. I have already had the disgusting experience of having an engineer come in and ask advice on some detailed phase of plotting a root locus plot only to find out gradually that the method had nothing to do with the problem he was supposed to solve!
>
> Fortunately however there are many students who make very reliable engineers once they understand the fundamentals of their subjects. I have tried in Chapter IV to present a chain of reasoning which will establish transfer functions and all their properties on the sure foundation of the solution to a few simple

differential equations by the classical method of trial and error. This chain of reasoning led to the development of root locus and it has often been of value in explaining the method. If the method of presentation is poor, I would surely appreciate criticism; but to substitute the Laplace transform in my present state of understanding of it would be unfair to the conscientious student for whom the book is intended.

The foundations of Evans' root-locus method and its presentation in *Control-System Dynamics* are traceable directly to lessons learned in General Electric's Advanced Course.

Two weeks after wiring Ziegler to destroy these remarks, Evans sent a muted version of his position in the only letter he ever addressed directly to Dean Terman. An attachment recounted specific experiences that led Evans to view the use of the Laplace transform as a contributing factor to the inability to work simple problems that required understanding and not rote learning.

As Thanksgiving Day in 1951 approached, two years after Evans signed the memorandum of agreement, the fate of Evans' manuscript was in doubt. Would McGraw-Hill even continue work on *Control-System Dynamics*? Their technical reviewer had criticized its presentation as outside the mainstream. Despite its later start, Thaler and Brown's servomechanism manuscript must have appeared more promising than that of Evans. Would McGraw-Hill reconsider the idea of including a Spirule with *Control-System Dynamics*, now that their own technical reviewer endorsed the idea? Ziegler answered some questions when, two days before Thanksgiving, he wrote these words of encouragement: "I would like to take this opportunity to tell you that we have received praise of your ability from several sources recently. The comments we have heard support the confidence we have placed in your successful completion of the project."

Ten days later, Ziegler informed him of Dean Terman's assessment, including the following excerpt from Terman's final review:

> Evans' viewpoint on the Laplace transform is a perfectly reasonable one. I think that some explanation about the place and usefulness of the Laplace transform and alternative methods should be incorporated somewhere in the book. If this is done, and Evans then wishes to leave out the Laplace transform completely, I would say fine and proceed on that basis.

Terman's favorable assessment reinvigorated Evans and McGraw-Hill to proceed. Happily, the AIEE had scheduled their annual conference for 6–7 December in Atlantic City, New Jersey. Evans proposed another face-to-face meeting on 5 December, the day he arrived in New York. It would be his first opportunity to meet Ken Ziegler and others on the editorial staff. He concluded his letter by again bringing up the Spirule: "The matter of enclosing the Spirule in the back cover of the book should perhaps be decided now, or at least all the facts presented. I will bring several of them with me also."

In New York Evans met the two men most involved with his project—Ken Ziegler and Jeff Norton, whom Ziegler had assigned to be the editor. Evans' handwritten notes from their meeting suggest that all of the men looked toward an early 1953 publication date with an initial printing of 2,000–3,000 copies. After consideration for the prospect of having to raise the book's price by $1.50 if the Spirule were included, Ziegler again advised Evans he would be better off selling it separately. Evans' notes read: "Recommends I sell it separately (May make as much as from royalties)." The Spirule matter was settled.

1952: A Critical Review

The prospects for *Control-System Dynamics* seemed as positive as personal dimensions of Evans' life in the winter and early spring of 1952. On 11 April he celebrated his tenth wedding anniversary. He had fulfilled his commitment to McGraw-Hill by completing all of the changes Dean Terman had required. Spirule sales were brisk; soon after the initial production run of 500 had sold out, Evans formed the Spirule Company as a mail order business out of his home in Whittier, California. Then, in the first week in June, the bottom fell out. In the same week that a life-threatening complication in wife Arline's pregnancy forced her hospitalization, Evans received a scathing review of his manuscript. In a diplomatic understatement, editor Ziegler simply wrote, "I am afraid that you will find his comments rather disappointing. It may be that he is a particularly severe critic."

The critic began his comments by acknowledging Evans' reputation, writing:

> His personality and his ability to think quickly have made a favorable impression at professional meetings. He has recently been appointed a member

> of the AIEE Committee on Feedback Control Systems. Because of this personal background, I looked forward to seeing a text by Mr. Evans.

He then delivered his critical assessment, writing:

> The basic conclusion of my review is that this book, if published in present form, would not do justice to the author's reputation. . . . It is not an easy task for a technical industrialist to find time to write a book. It is also difficult for someone as steeped as I in the field to review such a book with the proper perspective. While I think a stranger to the control field with only a general technical background would have a very difficult time with Mr. Evans' presentation, I am not at all sure of this. I am quite sure, however, that a scholar in the field would find too little new in this book by Mr. Evans.

However, his personal priorities reset by his wife's rapid recovery and the birth of their third child, Evans responded in a 24 June letter to Ziegler:

> The (critic's) comments . . . are not surprising; the disappointment to me is the time consumed in receiving reviews by one critic after another. The style and presentation has been set by five years of study and teaching in the General Electric Advanced Course, in which the prime object was understanding rather than rigor or elegance.

Time was of the essence. His editors had told Evans when he met with them in New York that they would need a final manuscript by summer to allow nine months to prepare the book for publication in time for professors to decide in the spring of 1953 whether they would use it in the fall. McGraw-Hill's editors, after consulting Dean Terman, asked Evans to respond only to comments that would not delay publication. However, the three months it took Evans to correct the manuscript effectively killed its chance of consideration for use in the 1953–1954 academic year.

A month later in November, Evans received his manuscript back, with the direction to retype portions of it, but another rollover of the calendar into 1953 would occur before Evans would get around to completing the changes. Having missed out on the opportunity to see the book selected for the next academic year, the book's priority had clearly slipped.

1953: Pushing Toward Completion

On 6 February Evans sent the retyped manuscript by Railway Express. He concluded his cover letter with a too-familiar line, "I hope that you will now find the manuscript completely satisfactory." Instead, McGraw-Hill's copyeditor Jeff Norton now turned Evans' attention to minutiae, and, in particular, the fine points of the rules for where to use hyphens. The editor argued for inserting a hyphen between *Control* and *System* in the book's title and between "root" and "locus" when associated with the "root-locus method." No fight left in him, Evans readily acquiesced.

Unsatisfied with some of Evans' sentence structures, Norton recommended that Evans share in paying the $200 costs associated with McGraw-Hill's use of a copyeditor. More weeks would go by. The copyeditor would be out sick for an entire month. In addition, Evans faced a publication deadline for a new root-locus paper directed at problems of interest to mechanical engineers [9]. The sense of urgency once shared by Evans and McGraw-Hill had long since dissipated. As 1953 came to a close, four years having elapsed since the project's start, McGraw-Hill had yet to complete its final version of the manuscript.

1954: Publication (at Last)

On 19 February, Jeff Norton informed Evans that the manuscript was in the printer's hands. The galley proofs were returned in mid-April. Distribution of the first printing of 2,500 copies of the book occurred on 30 September, and, on 28 November, Kenneth Ziegler wrote Evans to request corrections that could be accommodated in a planned second printing. On 11 December, Evans responded:

> The news that the total requirement for *Control-System Dynamics* might exceed 2,500 by the time second semester orders are placed is the biggest surprise that I have had for years. . . . Please have 12 (books) sent (to me) as quickly as possible because I want to send some of them out at Christmas.

After five years in the making, the book was not only published, but also headed for a second printing. Its cover page is shown in Figure 4.

Post-Publication Years

The goal Evans and McGraw-Hill had set for themselves in 1949—introduction of root locus into the college curriculum with a textbook capable of competing with Brown and Campbell—was realized in the 1950s, but not with *Control-Systems Dynamics*. After the publications of Evans' 1950 AIEE paper [3] and William Bollay's 14th Wright Brothers Lecture in 1951 [10], dozens of textbooks with chapters devoted to the root-locus method were published. The opening sentence in a November 1954 *Control Engineering* article summarized the situation Evans' new book faced:

> The engineer seeking an introduction, a review, or an upgrading of the basic theory of servomechanisms can choose from nearly a score of books written in English. . . . The books by Lauer, Lesnick, and Matson [11], by Trimmer [12], and Thaler [6] introduce the fundamental concepts, require limited mathematical

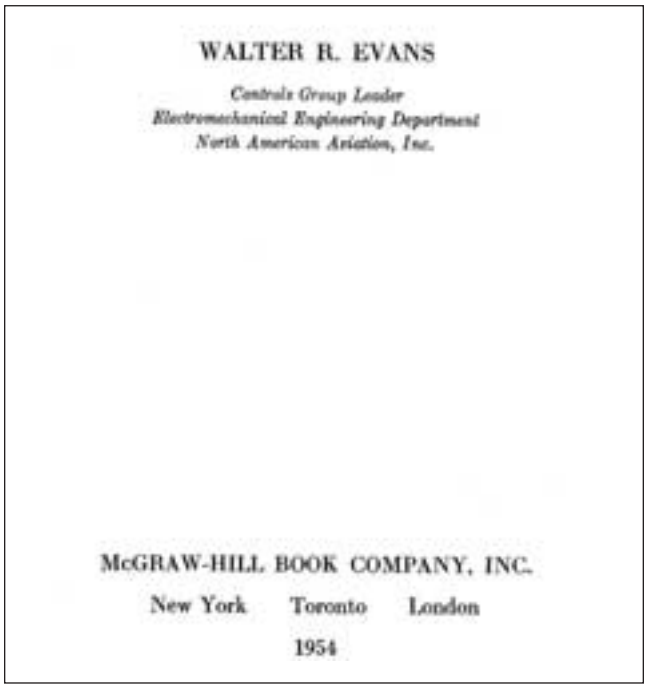

Figure 4. *The title page of* Control-System Dynamics. *On the subject of titles, Evans wrote to another author, Floyd Nixon, "I froze on the name in the early stages. The word 'dynamics' describes most of the emphasis in the text and avoids implications carried by such words as 'analysis,' 'synthesis,' or 'design.' In referring to books, most fellows I know usually just name the authors and probably couldn't name the title on a bet."*

> knowledge, and give a good briefing preliminary to the study of more comprehensive texts . . . [13]

These and other textbooks that followed brought the root-locus method into every college control systems classroom. George Thaler devoted the final chapter of his 1953 McGraw-Hill book to a 27-page explanation of the root-locus method. Upon his receipt of a copy from the publisher, Evans wrote to Thaler:

> I envy your opportunity to test the manuscript for three years with classes before publication. Having just taught from my book in a night course, I'm afraid it is too condensed . . . for many students. Another worrisome thing is that I have found several errors in the text without as yet having received any corrections from anyone.

Evans' worries were justified. After its initial spurt, sales of *Control-System Dynamics* dropped precipitously in the last half of 1955. By the end of the year, it would become clear to Evans and his publisher that other texts by other authors would become the basis for college students learning about Evans' method.

In 1955 McGraw-Hill itself would publish yet another important contribution to the field with *Automatic Feedback Control System Synthesis* by John G. Truxal, by then chairman of the Department of Electrical Engineering at the Polytechnic Institute of Brooklyn. His 57-page chapter on root locus would become one of the most popular textbook treatments of the method. Truxal wrote in its opening paragraph:

> . . .The root-locus method . . . combines the theoretical advantage of simultaneous control over both transient and frequency response of the system with a strong appeal to the designer, an appeal which is derived from the simplicity of the method as well as the logic underlying the approach. [14]

On 3 January 1956, Evans again wrote Kenneth Ziegler, his editor:

> The rapid decrease in sales is of course disappointing although I realize that there are many more books available now than last year. . . Comments I have received on the book are: "too brief", "excellent after you already understand the subject"! I was amazed in teaching the course again how much students want to have every step detailed for them. The unfortunate thing is that they won't get problems that clear-cut in industry and had better get into the habit of filling in the details.

Ziegler acknowledged in his response that the majority of sales were coming outside of their college text adoption area, with 2,527 sold by the Industrial and Business Books Department, the Trade Department, and International Department. He went on with the encouraging words:

> In view of the number of books already available, I think the record of your text is an excellent one. Further, I gather from several people I've talked to that your text appeals most to the mechanical engineers and as yet they are the lowest in the number of courses and enrollments in these courses.

In 1956 about 1,000 books sold; in 1957, sales dropped to 500. Over the four-year run from 1954 to 1957, McGraw-Hill sold about 5,000 copies with Evans receiving a net royalty of about $0.50 per book.

In September 1956, in his last letter to Ken Ziegler, Evans wrote, "Your advice certainly was right that the Spirule business might be more active than the book. Sales continue to grow slightly and are at about 1,000 per year." Indeed, sales would continue to increase, reaching their peak in 1965 with the sale of 7,500 units. From 1950 to 1980 Evans would sell over 100,000 Spirules to all 50 states and 75 countries.

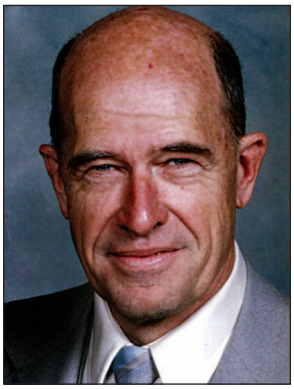

Figure 5. *Walter R. Evans as an engineer in 1980. This photograph was taken a few months before Evans suffered a stroke at age 60, which abruptly concluded his distinguished career with North American Aviation. He received the Rufus Oldenberger Medal from the ASME in 1987 and the Richard E. Bellman Control Heritage Award by the American Control Council in 1988. Throughout his 19 years of forced retirement, his wife Arline provided him frequent opportunities to swim, draw, play chess, and enjoy their four children and five grandchildren.*

Evans (Figure 5) had reason to be satisfied with his book. McGraw-Hill's consulting editor Fred Terman had permitted him to hold firm to principles he had learned from Prof. Roy Glasgow and Prof. Frank Bubb and mastered in Robert Doherty's Advanced Course. The book emphasized the physical picture and prepared the reader for complex problems using simpler examples. Evans had summarized its key features for McGraw-Hill in preparation for the publisher's post-publication advertising campaign:

> The main feature of the presentation is that the physical picture of a solution is developed first with the mathematics introduced later as needed. The opening chapters 1 and 2 describe the overall problem and the characteristics of typical components. The main purpose of the book (Chapters 3 though 10) is to demonstrate the techniques for determining the response of a linear control system. The simplest problem considered is the speed of a motor to a suddenly applied voltage; the most complex problem is the interaction of the roll and yaw motions of an airplane. Each solution establishes a concept that permits a simpler technique to be applied to the next more complicated problem.

Prospective textbook authors today face the same truth Evans faced—no book can substitute for a creative, one-on-one relationship between teacher and pupil. The mysteries of the educational process fascinated Walter Evans for years after he had written *Control-System Dynamics*. In a 1965 letter to Prof. Roy Glasgow on the occasion of Glasgow's retirement as dean of the Naval Postgraduate School, Evans summarized his observations as follows:

> Thinking about our four children, it seems to me that the real bulk of learning takes place in self study and problem solving with a lot of positive feedback around that loop. The function of the teacher is to pressure the lazy, inspire the bored, deflate the cocky, encourage the timid, detect and correct individual flaws, and broaden the viewpoint of all. This function looks like that of a coach using the whole gamut of psychology to get each new class of rookies off the bench and into the game.

In September 2004, 50 years after the publication of *Control-System Dynamics* [15], the game continues, and eager new students await their chance to get off the bench.

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