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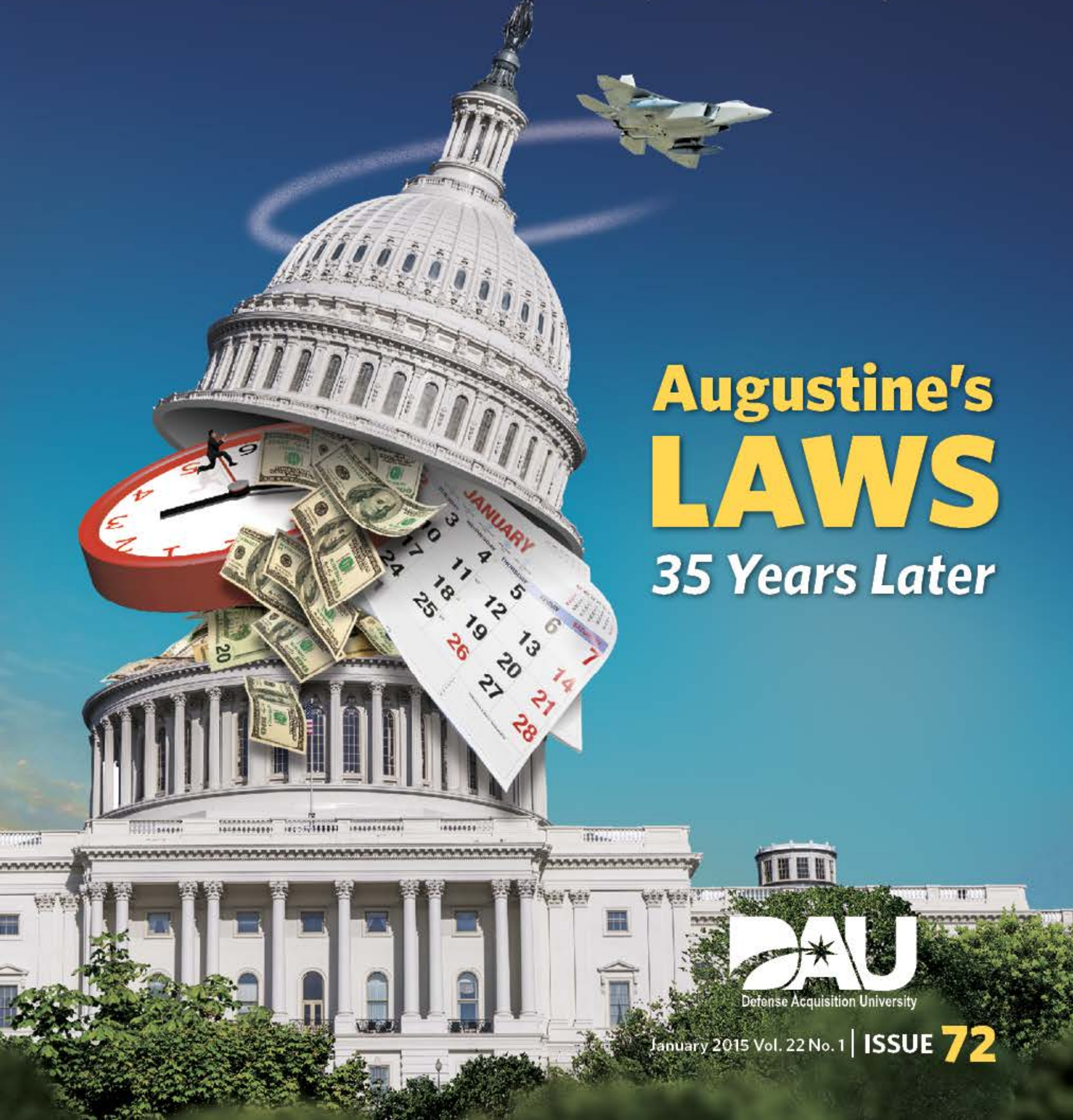
Defense Acquisition Research Journal

A Publication of the Defense Acquisition University



Augustine's LAWS

35 Years Later

DAU Defense Acquisition University

January 2015 Vol. 22 No. 1 | ISSUE 72

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **JAN 2015**	2. REPORT TYPE	3. DATES COVERED **00-00-2015 to 00-00-2015**
4. TITLE AND SUBTITLE **Defense Acquisition Research Journal**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Defense Acquisition University,,Attn: DAU Press, 9820 Belvoir Rd., Ste 3,,Fort Belvoir,,VA,22060**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
Defense ARJ, January 2015, Vol. 22 No. 1 : 2-63

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**171**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

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Defense Acquisition Research Journal

A Publication of the Defense Acquisition University

ISSN 2156-8391 (print) ISSN 2156-8405 (online)

The *Defense Acquisition Research Journal*, formerly the *Defense Acquisition Review Journal*, is published quarterly by the Defense Acquisition University (DAU) Press. Postage is paid at the U.S. Postal facility, Fort Belvoir, VA, and at additional U.S. Postal facilities. Postmaster, send address changes to: Editor, Defense Acquisition Research Journal, DAU Press, 9820 Belvoir Road, Suite 3, Fort Belvoir, VA 22060-5565. Some photos appearing in this publication may be digitally enhanced.

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Defense Acquisition Research Journal

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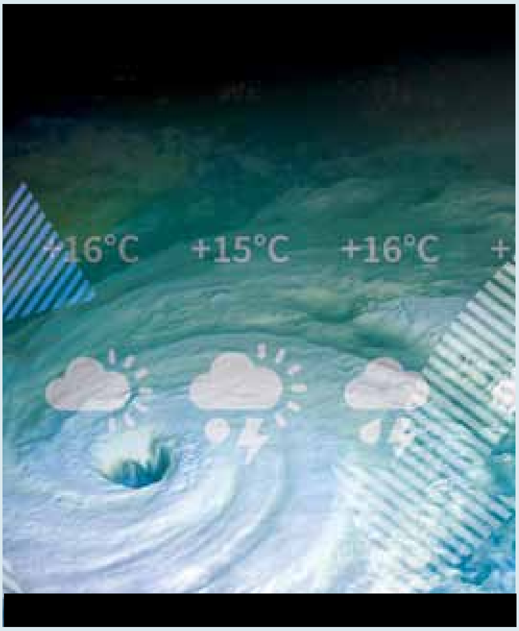

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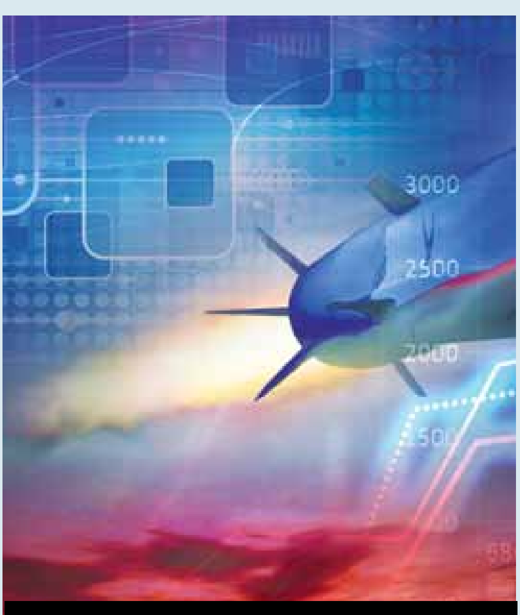
Taming the Hurricane of Acquisition Cost Growth —Or at Least Predicting It

Capt Allen J. DeNeve, USAF,
Lt Col Erin T. Ryan, USAF,
Lt Col Jonathan D. Ritschel, USAF, and
Christine Schubert Kabban

A regression technique is used to predict cost growth in new acquisition programs by associating these programs with previous ones. This technique reduces cost estimate error in the earliest estimates by over one third.



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The Effects of System Prototype Demonstrations on Weapon Systems Development

Edward J. Copeland, Thomas H. Holzer,
Timothy J. Eveleigh, and
Shahryar Sarkani

The findings from this research indicate that system prototype demonstrations do indeed have a profound positive influence on the outcome of weapon systems development performance.

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CALL FOR AUTHORS

We are currently soliciting articles and subject matter experts for the 2015–2016 *Defense Acquisition Research Journal* (*ARJ*) print years. Please see our guidelines for contributors for submission deadlines.

Even if your agency does not require you to publish, consider these career-enhancing possibilities:

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We welcome submissions from anyone involved with or interested in the defense acquisition process—the conceptualization, initiation, design, testing, contracting, production, deployment, logistics support, modification, and disposal of weapons and other systems, supplies, or services (including construction) needed by the DoD, or intended for use to support military missions.

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FROM THE CHAIRMAN AND EXECUTIVE EDITOR

Dr. Larrie D. Ferreiro

The year 1979 was marked by the invasion of Afghanistan by the Soviet Union, the Iranian Revolution that overthrew the Shah and held 52 American diplomats hostage, and the election of Margaret Thatcher as Prime Minister of the United Kingdom. The Sony Walkman was introduced to a transfixed public, but at a price equal to almost a week's wages. The entire federal budget was roughly $500 billion, a number now equated with just the Department of Defense portion of the budget.

The year was also marked by the first full publication of the now-legendary "Augustine's Laws and Major System Development Programs" in the pages of the *Defense Systems Management Review*, and a few years later in *Concepts*, the journals that preceded the current *Defense Acquisition Research Journal*. Norm Augustine, at the time a member of the journal's Editorial Board and a Vice-President at Martin Marietta Aerospace, was well known in the defense acquisition community, having served in several senior leadership positions in the Department of Defense and industry.

Although Augustine's Laws were written in a somewhat tongue-in-cheek fashion, they are quite serious. We are proud to republish them 35 years later, and delighted that he has agreed to pen a short introduction looking back at how they have held up over time. His most famous law, on the increasing cost of tactical aircraft, can now fix the precise date on which the entire defense budget will buy just one airplane. We are even provided a glimpse into future laws.

In this issue we are also pleased to publish the research of several teams of researchers who are extending the boundaries of our knowledge in defense acquisition. Alex Miller and Joshua L. Ray, in "Moving from Best Practices to Standard Practices in Defense Acquisition," examine the DoD's difficulty in translating observed best practices into consistently applied acquisition processes and provide a simple framework to assess the standardization of these practices. Capt Allen J. DeNeve, USAF, Lt Col Erin T. Ryan, USAF, Lt Col Jonathan D. Ritschel, USAF, and Christine Schubert Kabban, in "Taming the Hurricane of Acquisition Cost Growth—Or at Least Predicting It," provide a statistically derived approach to forecast how a program's baseline is likely to change over time, instead of assuming it will remain static, which promises to improve the prediction of a program's likely cost growth and thus to develop more realistic cost estimates.

In "The Effects of System Prototype Demonstrations on Weapon Systems Development," Edward J. Copeland, Thomas H. Holzer, Timothy J. Eveleigh, and Shahryar Sarkani find that system prototyping positively influences the outcomes of weapon systems development programs—a key finding that helps support recent Better Buying Power initiatives promulgated by Under Secretary of Defense for Acquisition, Technology, and Logistics Frank Kendall to incentivize innovation in both government and industry.

Finally, we acknowledge the hard work and dedication of three departing members of the *Defense Acquisition Research Journal*'s Editorial Board: Dr. J. Robert Wirthlin of the Air Force Institute of Technology, Dr. Donald Hutto of the Defense Acquisition University, and Dr. Mark Montroll of the Dwight D. Eisenhower School for National Security and Resource Strategy. We also welcome three new members to the Board: Dr. John M. Colombi of the Air Force Institute of Technology, and Professors John Cannady and Dana Stewart, both of the Defense Acquisition University South Region in Huntsville, Alabama. We look forward to their contributions.

DAU CENTER FOR DEFENSE ACQUISITION RESEARCH

RESEARCH AGENDA 2015

The Defense Acquisition Research Agenda is intended to make researchers aware of the topics that are, or should be, of particular concern to the broader defense acquisition community throughout the government, academic, and industrial sectors. The purpose of conducting research in these areas is to provide solid, empirically based findings to create a broad body of knowledge that can inform the development of policies, procedures, and processes in defense acquisition, and to help shape the thought leadership for the acquisition community.

Each issue of the *Defense ARJ* will include a different selection of research topics from the overall agenda, which is at: http://www.dau.mil/research/Pages/researchareas.aspx

Measuring the Effects of Competition

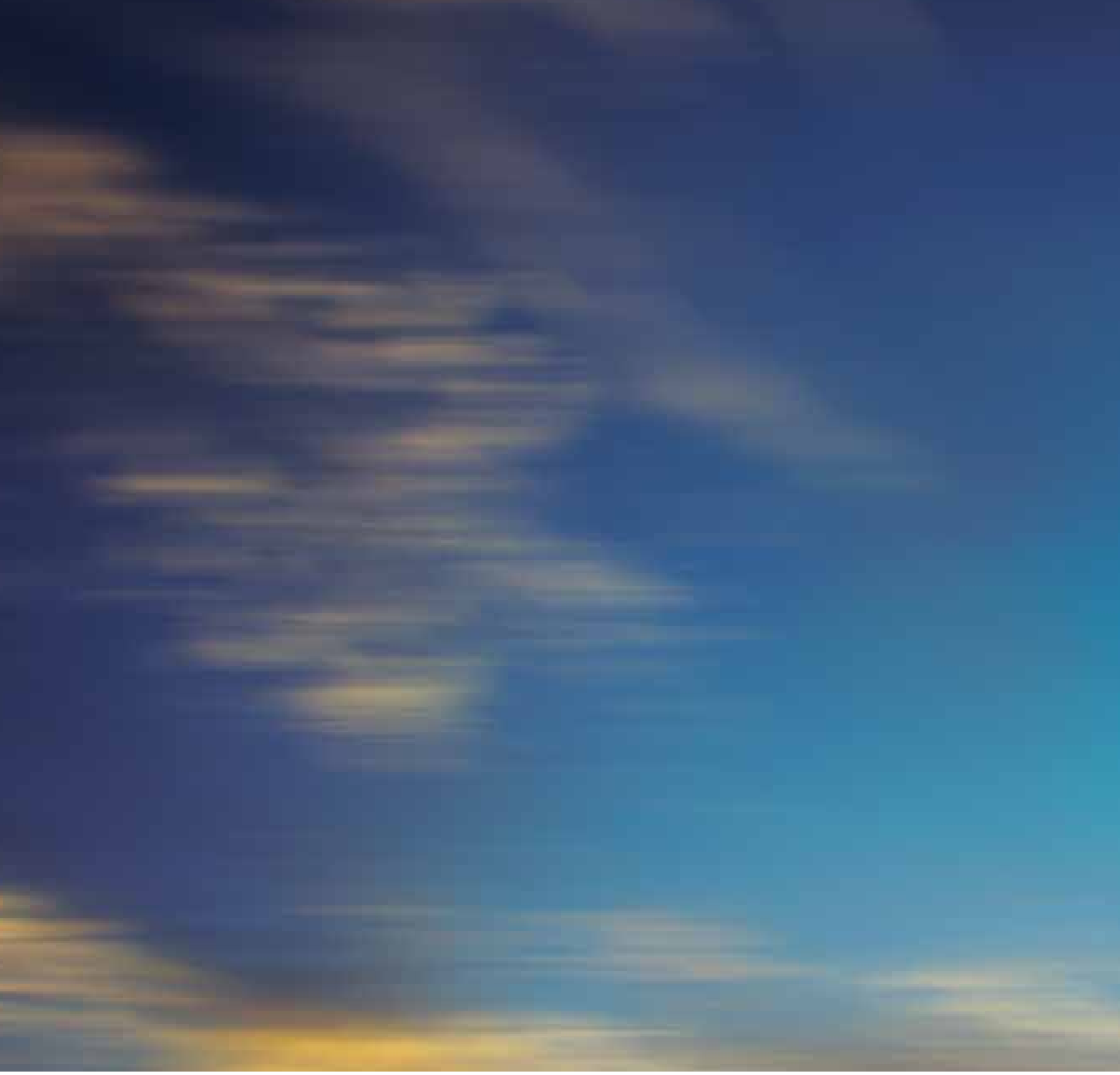
- What means are there (or can be developed) to measure the effect on defense acquisition costs of maintaining an industrial base in various sectors?

- What means exist (or can be developed) of measuring the effect of utilizing defense industrial infrastructure for commercial manufacture in growth industries? In other words, can we measure the effect of using defense manufacturing to expand the buyer base?

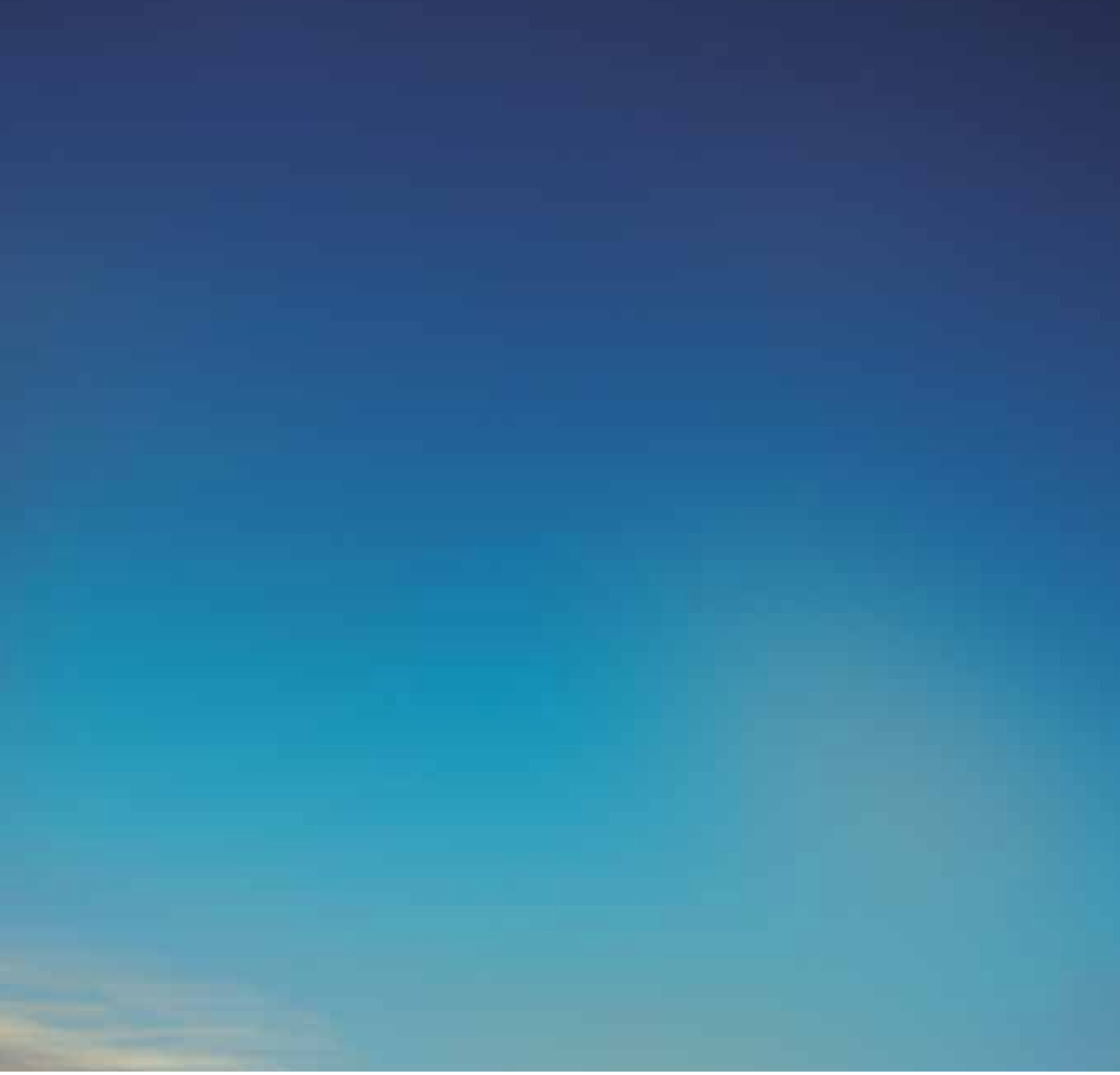
- What means exist (or can be developed) to determine the degree of openness that exists in competitive awards?
- What are the different effects of the two best-value source-selection processes (tradeoff vs. lowest price technically acceptable) on program cost, schedule, and performance?

Strategic Competition

- Is there evidence that competition between system portfolios is an effective means of controlling price and costs?
- Does lack of competition automatically mean higher prices? For example, is there evidence that sole source can result in lower overall administrative costs at both the government and industry levels, to the effect of lowering total costs?
- What are the long-term historical trends for competition guidance and practice in defense acquisition policies and practices?
- To what extent are contracts being awarded noncompetitively by congressional mandate, for policy interest reasons? What is the effect on contract price and performance?
- What means are there (or can be developed) to determine the degree to which competitive program costs are negatively affected by laws and regulations such as the Berry Amendment and Buy American Act?



ISSUE 72
JANUARY 2015
VOL. 22 NO. 1



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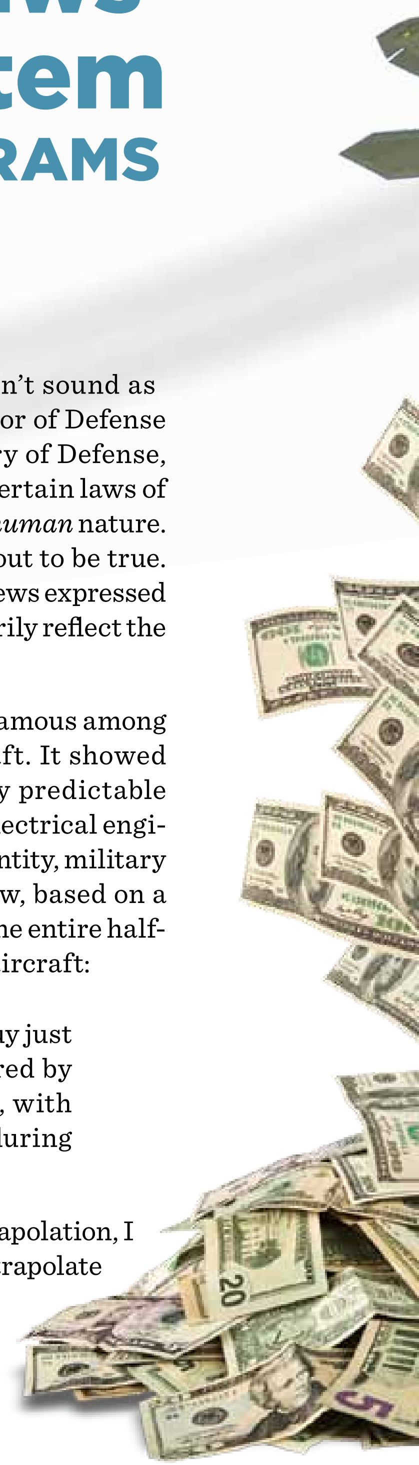
Preface:

Augustine's Laws and Major System DEVELOPMENT PROGRAMS

by Norman R. Augustine



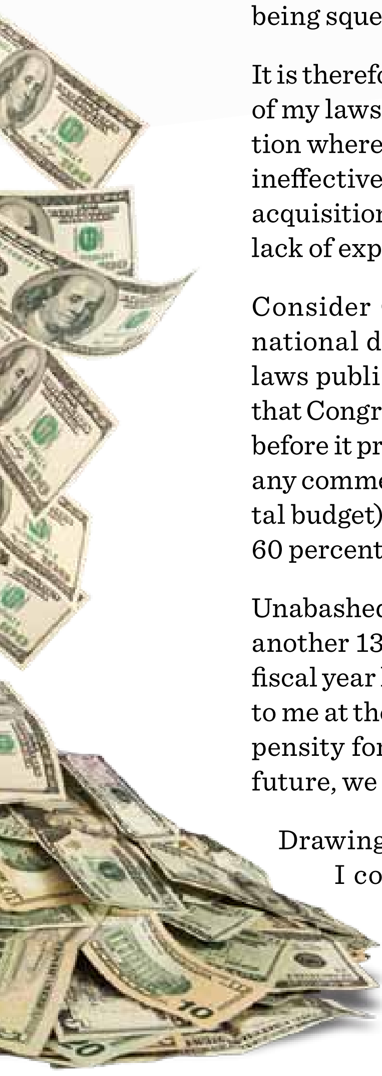
Two score and eight years ago (somehow that doesn't sound as long as 48 years ago), I was working as Assistant Director of Defense Research and Engineering in the Office of the Secretary of Defense, and it occurred to me that just as physical systems obey certain laws of nature, perhaps defense acquisition obeys certain laws of *human* nature. To my amazement—and everlasting regret—this turned out to be true. (Caveat: To protect the innocent as well as the guilty, the views expressed in *Augustine's Laws* are purely my own and do not necessarily reflect the views of my employers—past, present, or future.)

The earliest of my immutable laws—perhaps the most infamous among them—addressed the increasing cost of tactical aircraft. It showed that the unit cost of such machines increases at a very predictable rate—a factor of four every 10 years (6 db/decade for the electrical engineers)—independent of everything else (performance, quantity, military department, inflation, etc.). This led to the following law, based on a straightforward extrapolation of the defense budget and the entire half-century's experience then available in building military aircraft:

> In the year 2054, the entire defense budget will buy just one tactical aircraft...which will have to be shared by the Navy and the Air Force 6 months each year, with the Marine Corps borrowing it on the extra day during leap years.

Recognizing that this represents a not inconsiderable extrapolation, I rationalized that economists in Washington frequently extrapolate based on a *single* data point.

Fast-forwarding to today, *The Economist* magazine recently devoted a full page to updating this law, which was initially promulgated in 1967 (and published 35 years ago in the *Defense Systems Management Review*). *The Economist*'s analysis confirmed that the prediction is still right on track. In fact, it is now possible to refine the previously projected 2054 date: it will actually be *July 23*, 2054. Indeed, the number of aircraft being built each year has declined precipitously (96,000 per year at the peak of World War II) and, as predicted by Law XIV—using Roman numerals makes it seem more profound—the pilots of said aircraft are gradually being squeezed right out of the cockpit.

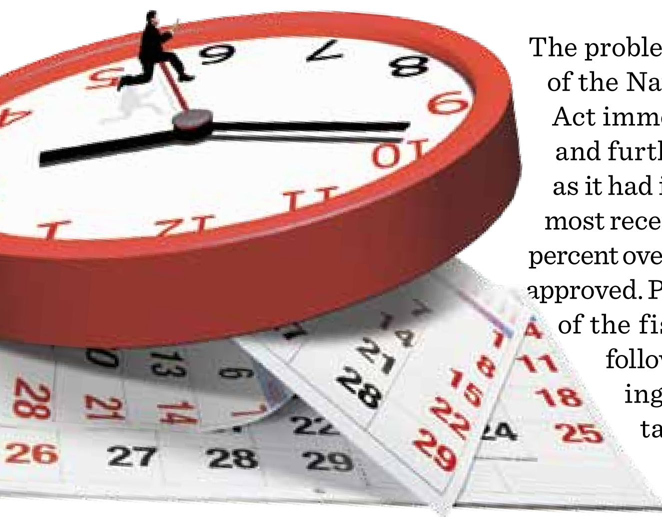


It is therefore with considerable regret that one must conclude that most of my laws have in fact withstood the test of time. The principal exception wherein they seem to have missed the mark is my projection of the ineffectiveness of Congress in carrying out its principal role in defense acquisition—an attainment that has considerably underperformed my lack of expectations.

Consider Congress's major responsibility to produce a budget for national defense as assigned in the Constitution. In my initial set of laws published in *Defense Systems Management Review*, it was noted that Congress was slipping later and later into each successive fiscal year before it produced an operating budget (note that in contrast to virtually any commercial firm, Congress does not even attempt to produce a capital budget). Finally, the point was reached in the mid-1970s where fully 60 percent of a year had passed before a budget was provided.

Unabashedly extrapolating the above trend, I was able to predict that in another 13 years from that time no budget would be provided until the fiscal year had passed into history. As a Russian acquaintance explained to me at the end of the Cold War, speaking in his case of his nation's propensity for historical revisionism, "Not only do we have an uncertain future, we have an uncertain past."

Drawing—incorrectly as it turned out—on my experience in industry, I concluded that this level of nonperformance would prompt an immediate uprising on Capitol Hill that would focus on discipline, accountability, and consequences throughout the legislative process. But as it turned out, the legislative branch had a far more imaginative solution to the dilemma than merely implementing the principles of Management 101. Instead, in 1976 Congress simply *redefined* the fiscal year, slipping it by 3 months…thus (presumably), making it possible to produce a budget on time once again (overlooking the minor arithmetical inconsistency inherent in this illogic).



The problem, of course, was that the date of the National Defense Appropriations Act immediately began slipping further and further into the *new* fiscal year just as it had in the *old* fiscal year, until in the most recent 5-year period the year was 38 percent over, on average, before a budget was approved. Presumably, another redefinition of the fiscal year will be forthcoming, followed by yet another, thus providing a never-ending solution to the tardy-budget dilemma—a sort of self-eating watermelon.

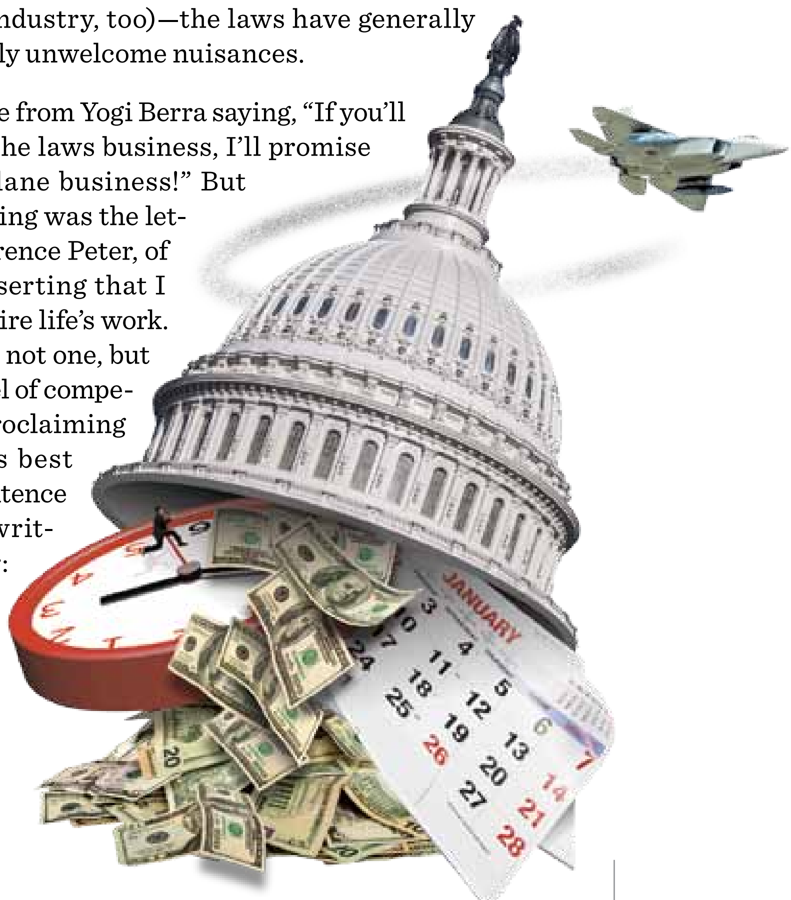
On the other hand, Congress has done a rather good job of placing demands on others. For example, over the most recent one-third of a century the number of reports it requires the Executive Branch to submit by a certain date has increased by no less than 351 percent. And in its newly available free time the Congress has increased the income tax code from a mere 16 pages 80 years ago to 45,622 pages today—while legislating that ignorance of the law is no excuse.

The original bookform of *Augustine's Laws,* now published in six languages, contained 52 laws. But, it has turned out that creating laws is such a target-rich battlefield that I have now collected more than enough material to proclaim yet another 52 laws—but, probably fortunately, with no time to record them.

Many of the original laws about defense acquisition have actually been found to have application to a wide range of fields, spanning from healthcare to education and well beyond. Consider, for example, the difficulty of producing more engineers—a profession critical to the defense acquisition process. Of the 93 nations evaluated in one recent study, the fraction of baccalaureate degrees going to engineers placed the United States solidly in 79th place (most closely matching Mozambique). Worse yet, the National Assessment of Educational Progress (NAEP) standardized test scores in mathematics for U.S. high school students have not improved in the past half-century, even though public school spending per student has grown markedly. Thus, in 1970 it cost just $15.30 per student per point scored on the NAEP mathematics test, whereas today the cost is $36.07 (in constant dollars). This does not seem to bode well for the future of defense acquisition...or, for that matter, the nation's economy. One creative solution would, of course, be to increase the maximum number of points that could be scored on the examination.

When I first began publicly proclaiming laws about the failures of industry and government it, perhaps not unreasonably, stirred a degree of angst on the part of my employer. I was reminded that, being a defense contractor, people who live in glass houses should not throw stones... or something to that effect. However, other than one minor episode—a friend of mine, then Chief of Staff of the Army, took public umbrage at the law I had endorsed, which states that "Rank times IQ is a constant" (sadly, this applies in industry, too)—the laws have generally been embraced as merely unwelcome nuisances.

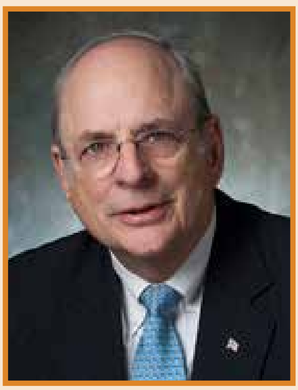
I actually received a note from Yogi Berra saying, "If you'll promise to stay out of the laws business, I'll promise to stay out of the airplane business!" But much more condescending was the letter I received from Laurence Peter, of the Peter Principle, asserting that I had undermined his entire life's work. He said that I had risen not one, but two levels above my level of competence. This hazard of proclaiming new laws was perhaps best described in a three-sentence essay about Socrates written by a fourth-grader: "Socrates was a philosopher," she wrote. "He went around telling people what was wrong. They fed him hemlock."



Whatever the case, the gauntlet laid down by *Augustine's Laws* seems to be more relevant today—and certainly more demanding—than was the case at the time they were conceived. And, for the record, my newest law goes as follows:

> If you send money to the management of a project that is in trouble, they will remember you the next time they need money.

You first read it here.



Norman R. Augustine

Mr. Augustine is retired Chairman and CEO of Lockheed Martin and served as Under Secretary of the Army, Chairman of the American Red Cross, President of the Boy Scouts, Chairman of National Academy of Engineering, Defense Science Board, and American Institute of Aeronautics and Astronautics. He is a holder of National Medal of Technology and five-time recipient of the Department of Defense Civilian Distinguished Service Medal. Mr. Augustine is the recipient of 33 honorary doctorates and served as Trustee of Princeton, MIT, and Johns Hopkins and Regent of University System of Maryland.

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DEFENSE SYSTEMS MANAGEMENT REVIEW

SPRING 1979
VOLUME 2
NUMBER 2

Augustine's Laws and Major System Development Programs

50

Norman R. Augustine

Insight into the problems of program management is sometimes found in unexpected places. For example, A. A. Milne could well have been writing about the sufferings of managers of large system development activities in the opening paragraph of *Winnie-the-Pooh*. "Here is Edward Bear," he wrote, "coming downstairs now, bump, bump, bump, on the back of his head, behind Christopher Robin. It is, as far as he knows, the only way of coming downstairs, but sometimes he feels that there really is another way...if only he could stop bumping for a moment and think of it!"

Indeed, there *is* a better way, as innumerable highly successful programs have demonstrated. Still, there remains that large set of much maligned projects which, were they ever to be documented into a movie, might best be viewed with the film run backward in order to ensure a happy ending. It is largely from these programs that Augustine's Laws have been formulated. The laws are dedicated to the proposition that with a better understanding of the history of past programs, one need only selectively repeat history in the future. Further, it is suggested that the behavior of large system management activities is as amenable to analysis as are most of the systems themselves. Each of the 15 laws, with a sample of the evidence supporting its existence, is examined in the following paragraphs.

Employer of Only Resort

Law Number I corroborates the late Senator Everett Dirksen's observation about big government: "A billion here, and a billion there," he stated, "and pretty soon it adds up to real money."

The percentage of civilian workers in the United States employed by government at the Federal, State and local levels is displayed in Figure 1. A growth trend is observed which has been very predictable and monotonic throughout the history of the nation. A modest extrapolation into the future, shown by the dotted portion of the trend line, indicates that the time is not too distant when one

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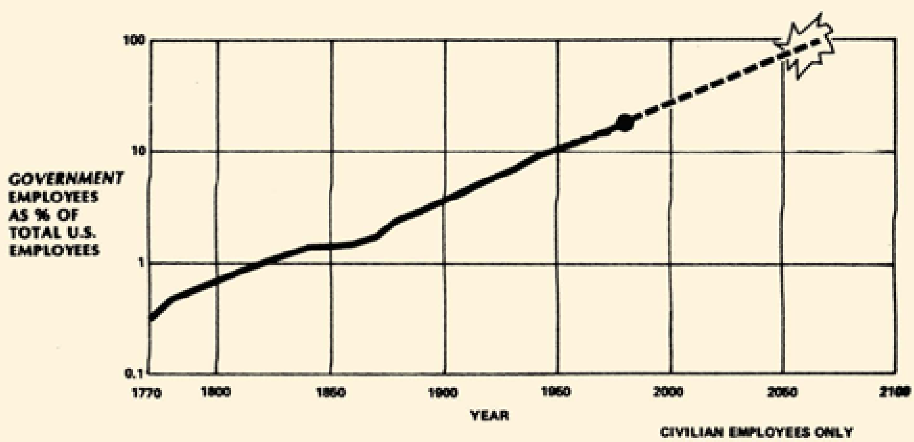
Author's Note: "Augustine's Laws" are intended to help explain the tribulations of program management. They have been formulated over a period of years and are based on observations of a large number of actual development programs. Although some of the laws have been published previously, this is the first time that all 15 laws have been collected as an entity.

Norman R. Augustine is Vice President of Martin Marietta Aerospace responsible for research, development and manufacturing. He has served as Under Secretary of the Army, Assistant Secretary of the Army for Research and Development, and as Assistant Director of Defense Research and Engineering in the Office of the Secretary of Defense. His recognition in 1976 of the need for a publication devoted to the concerns of those involved in acquisition management resulted in the establishment of the Defense Systems Management Review. *He continues to serve the* Review *as a member of the Editorial Board. Mr. Augustine holds B.S.E. and M.S.E. degrees in aeronautical engineering from Princeton University.*

FIGURE 1
Growth of Government



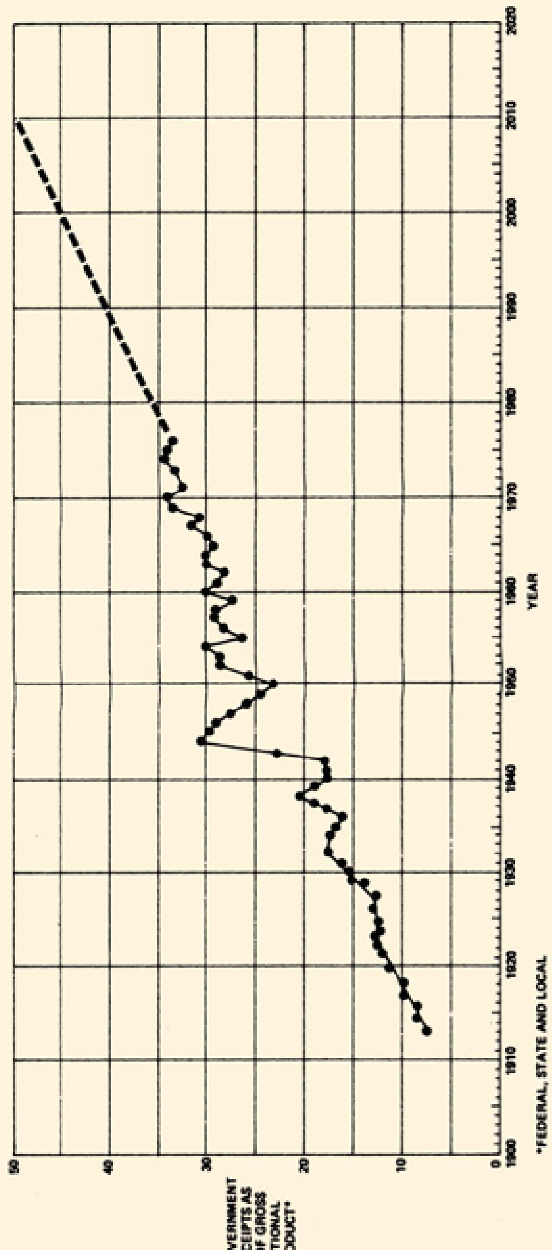
should expect 100 percent of the working population to be working for the government. Taking the next logical step, one can then state Augustine's First Law:

> **I: By the time of the nation's tricentennial, there will be more government workers in the United States than there are workers.**

For What It's Worth, Save Your Money

This trend in the growth of government as measured by the number of people it employs is, of course, paralleled by the government's financial receipts; and in turn by the government's ability even to conduct its own programs on its own behalf as it sees fit. For example, there is now a tax collector somewhere in the U.S. extracting a dollar every 25 milliseconds—including roughly half of each dollar of the profits earned by industry. By extrapolating the trend shown in Figure 2, it can be seen that the government will have all the money that is generated in the U.S. economy by the year 2120 and, as has already been noted, it will directly employ all the people about 60 years prior to that time. What happens during the interim period between these dates is not yet clear, but poses the interesting question of whether the last person left in the private sector will have to support the entire nation's work force, or whether he or she instead will individually enjoy the full benefit of those residual funds not yet controlled by the

FIGURE 2
The Demise of Free Enterprise



government. Whatever the explanation, this uncertainty leads to the guarded optimism expressed in Law Number II, actually the corollary to the first law, which is:

II: People working in the private sector should try to save money if at all feasible. There remains a possibility that it may someday be valuable again.

In terms of the fraction of the gross national product absorbed in the form of government receipts, one can also use the extrapolation presented in Figure 2 to ascertain that the U.S. lags England by only 17 years and Sweden by only 56 years in this respect.

The significance of these observations to an industrial program manager is obvious. Their significance to a government program manager, although perhaps less obvious, is nonetheless every bit as significant; namely, competition among potential sources is the essence of a program manager's leverage, and the absence of a multiplicity of strong competitors can only lessen the government program manager's chances of success.

On Striving to Be Average

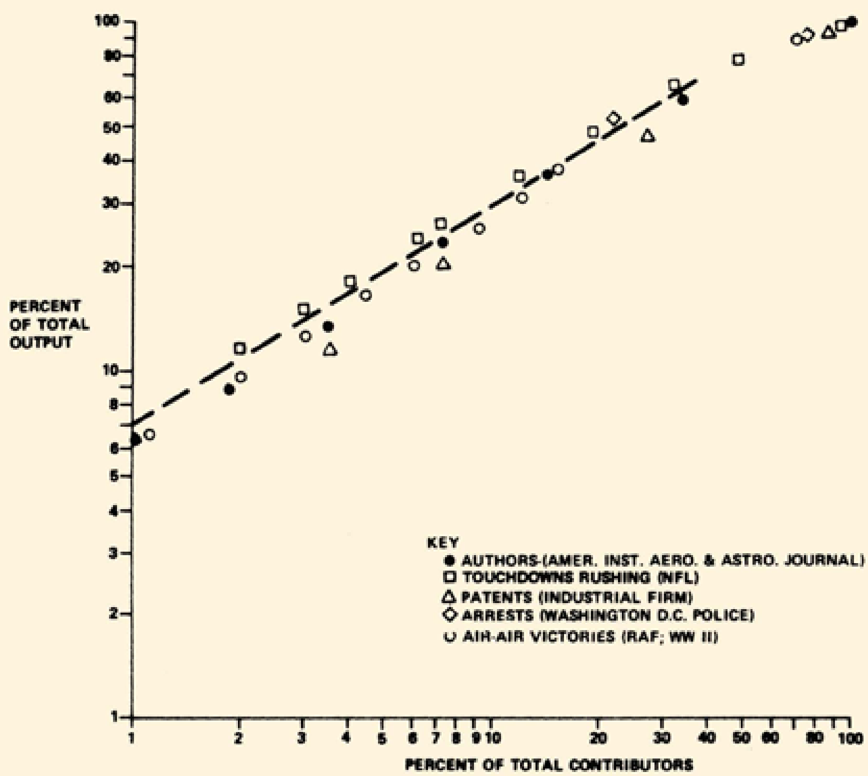
Law Number III confirms the suspicion that very few people come up to the average.

The contribution made by a group of people working in a common endeavor tends to be highly concentrated in the achievements of a few members of that group. The degree of this concentration is observed to obey a fundamental law, as indicated by the data in Figure 3. It is seen that the great predominance of output is produced by a disproportionately small segment of the participants, with the same law seeming to apply whether one is addressing authors, pilots, engineers, policemen, or football players. As one "digs deeper into the barrel," so to speak, in order to increase the manning of a given task, the average output is merely driven downward and, ultimately, large numbers of participants are added with hardly any increase in productivity at all (unless, of course, changes in work methods are also introduced). Conversely, substantial reductions in manning—eliminating the least productive contributors—can be made with little impact on overall output. In fact, the least productive half of all participants seems to generate *no more* than 20 percent of the total output.

It might be more accurate to describe the above observation as merely a generalization or corollary of V. Pareto's work published in 1897, in which it was demonstrated that the proportion of people with an income N was proportional to $1/N^{1.5}$.

The results presented in Figure 3 are probably understated, since the data base considers only participants who made at least *some* contribution, such as obtaining one patent, when in reality there are many who obtained *no* patents. Further,

FIGURE 3
Concentration of Productivity



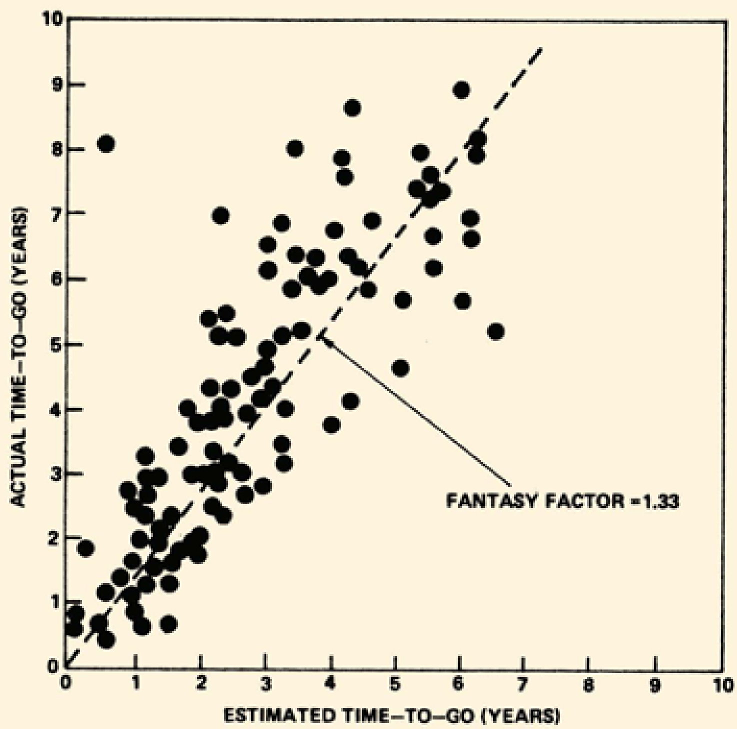
there are unquestionably those who produce negative output, such as the worker who makes so many mistakes that a great deal of the time of other potentially productive workers is consumed in rectifying the problems the former has created. Only about one-third of the workers typically achieve a level of contribution equal to the average of all those who contribute.

This leads to the third law, which relates to the allocation of manpower and can be stated as follows:

III: One-tenth of the people involved in a given endeavor produce at least one-third of the output, and increasing the number of participants merely serves to reduce the average performance.

As has often been pointed out, when an individual item can only be produced at a financial loss, it is very, very difficult to make it up on volume.

FIGURE 4
Accuracy of Projecting Accomplishment Date for Major Milestones



The Reality of the Fantasy Factor

Law Number IV explains why one should never commit to complete a task within 6 months of the end of any fiscal year—in either direction.

In 1798, Eli Whitney contracted to deliver 10,000 muskets to the Continental Army within 28 months. As things worked out, he delivered them in 37 months, or in about one-third more time than had been anticipated.

During 1978, a number of new systems were delivered to the U.S. military forces by major defense contractors. On the average, according to the reports submitted to the Congress, these systems were delivered in about one-third more time than had been anticipated.

The fraction "one-third" seems to have scientific significance in determining the schedule error associated with predicting major program events (some say the correct number is actually more nearly equal to one over *pi*). The data shown in Figure 4 are derived from a large number of official schedule estimates predicting when various milestones, such as first flight, first delivery, etc., will occur. These data, in turn, form the basis for Law Number IV, which defines the concept of the Fantasy Factor:

IV: Any given task can be completed in only one-third more time than is currently estimated.

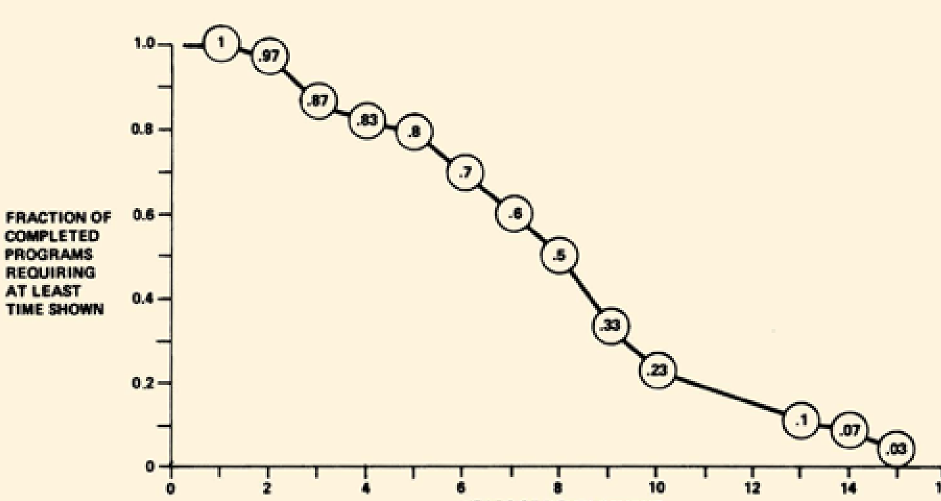
The above law addresses the accuracy of predicting how long it will take to reach any particular milestone in a development program's life. A different law addresses the overall trend of increasing time required actually to prosecute a development program. This latter issue is the subject of Law Number V.

So Old for Its Age

Law Number V, on program geriatrics, explains how World War II was won in about half the time it today takes to develop a new military system.

Figure 5 shows that the average major system development for national defense today takes slightly over 8 years to complete. Interestingly, the *doing* time, for example the time from the beginning of the design of a new airplane until its first flight, has not changed significantly during the last quarter of a century, as can be seen in Figure 6.

FIGURE 5
Duration of Development Programs



What *has* changed is the decision/approval time it takes to get a new program started, together with the time it takes to get it fielded once the development has been completed. The historical ratio of *planning* time to *doing* time for a number of major system developments is shown in Figure 7. On the average, the total time it takes to develop a new system, including decision and approval time, has been increasing at a rate of 3 months per year, each year, for the past 15 years.

Law Number V can then be stated, based in part on the fact that the half-life of most technologies has been determined elsewhere to be on the order of 10 years:

V: If current trends persist, most new systems will be obsolete only slightly before they are born.

Work and the Theory of Relativity

Law Number VI offers an alternative to the bus company serving the Bagnall to Greenfields route in England, whose spokesman recently countered criticism that half-empty buses were speeding past long queues of would-be riders with the explanation, "It is impossible for the drivers to keep their timetable if they have to stop for passengers."

In competitive, time-sensitive markets, managers are simultaneously challenged on three fronts. Not only must they produce a desirable product at a reasonable price, but in addition they must deliver their output to the

FIGURE 6
Trends in Development Time

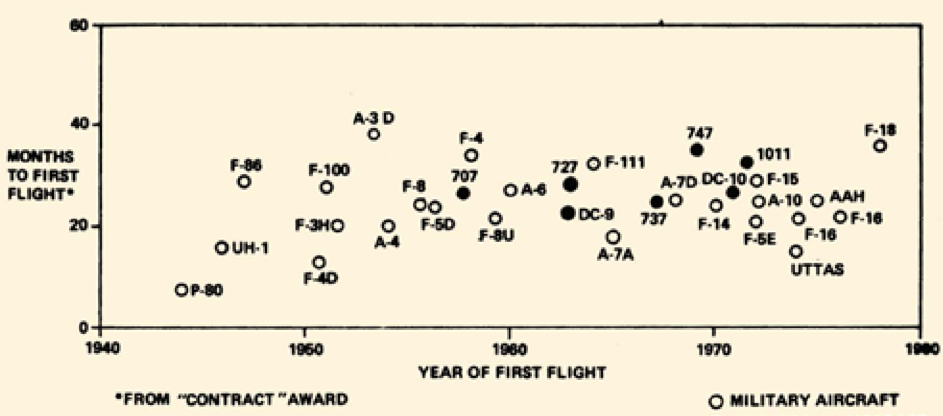
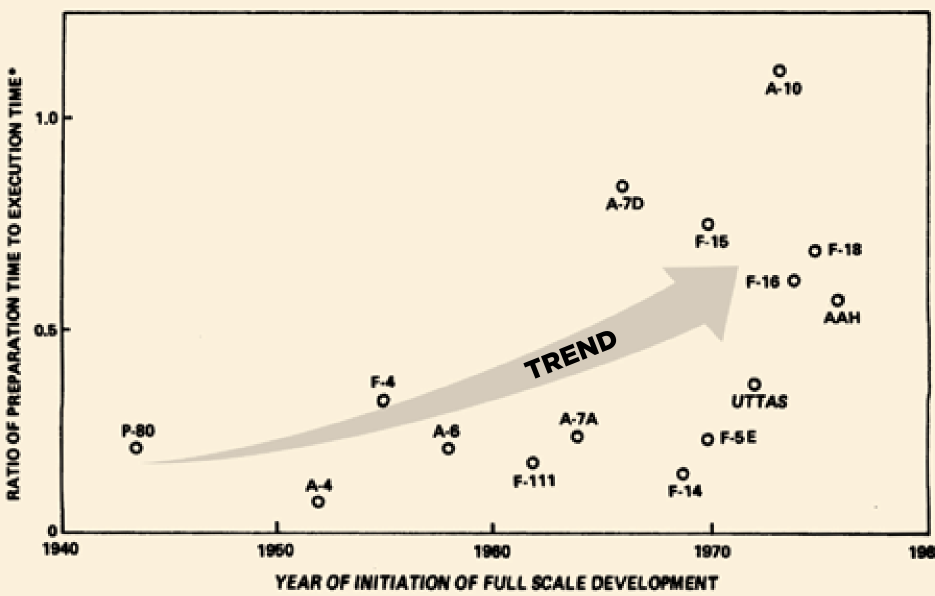


FIGURE 7
Relationship of "Decision" Time to "Doing" Time



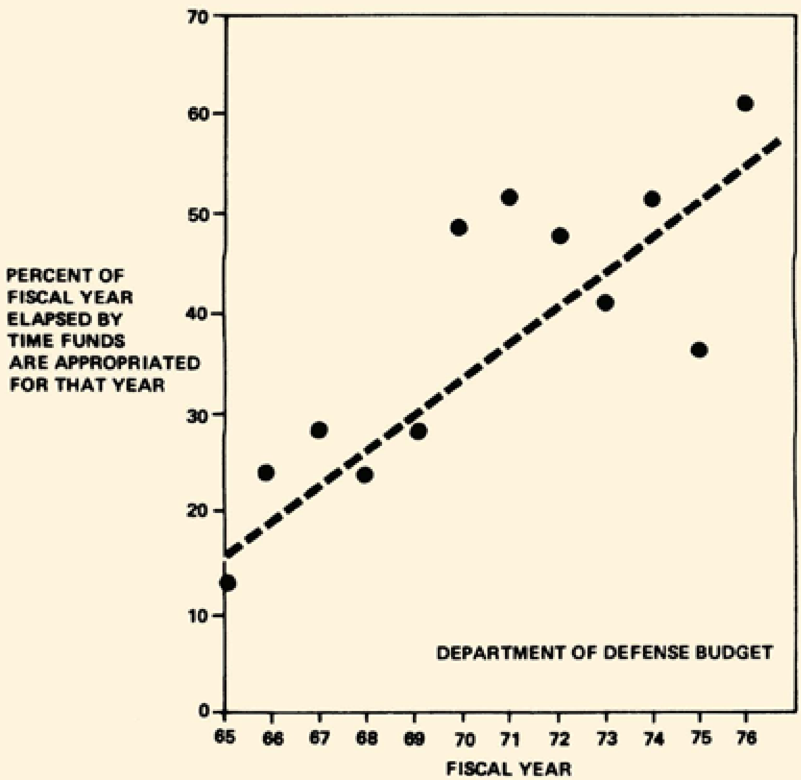
*DEFINED AS (TIME FROM CONCEPT FORMULATION TO START OF FULL SCALE DEVELOPMENT) DIVIDED BY (TIME FROM START OF FULL SCALE DEVELOPMENT TO INITIAL OPERATIONAL CAPABILITY)

marketplace in a timely manner. This urgency is characteristic of a large variety of products, irrespective of whether the aforementioned pressure arises from perishability of the product itself, the need to rapidly exploit some technological breakthrough, or merely to keep up with demand.

In environments wherein only one source of an item is available, however, an altogether different set of dynamics prevails. Consider, as but one example, the problem faced by the U.S. Congress as it each year, in addition to a myriad of other crucial tasks, pursues the matter of approving a budget for each of the Federal departments. For one reason or another, the Congress has apparently found it increasingly difficult to complete this task prior to the beginning of the year in which the money is to be spent.

The data in Figure 8 display how in each fiscal year the date at which funds are finally appropriated has tended to slide further and further into the year. This problem recently culminated, in the case of the defense budget, in a circumstance wherein the appropriation act did not become law until the year was more than

FIGURE 8
Increasing Length of Budget Approval Process



half completed! The challenge posed to those charged with executing that budget can, in fact, be accurately imagined...particularly those unfortunate managers whose requested budget was halved.

What the future portended for those same managers could be glimpsed by projecting forward in time the trend line in Figure 8. The inevitable conclusion seemed to be that it would be only about a decade until the situation reached crisis proportions; i.e., the budget would not be approved until the year was altogether past.

Fully recognizing this dilemma, the Congress proceeded to rectify the intensifying problem with both alacrity and decisiveness. Less imaginative managers in private industry, given the same circumstances, might have resorted to such conventional techniques as eliminating some of the 18 votes taken each year on large segments of the budget, or even to a process of expediting the budget cycle by combining various steps in the review process, or perhaps even by resorting to multi-year funding.

As luck would have it, however, no such pedestrian approaches were needed. The obvious solution, and that seized upon by the Congress, was, of course, to pass a law changing the definition of the fiscal year, hereafter slipping it neatly into compliance with the time it was actually taking to complete the task of preparing a budget.

The essential element that made this resolution of a nasty problem possible was, of course, the fact that there is only one Congress available, and if this one does not produce a budget act by any given time, there is no danger of another competitive Congress stepping in and producing one of its own. It can be safely inferred that such latitude for problem solving is by no means restricted to governmental bodies, but is attendant to any entity functioning in a sole-source environment.

Professor C. Northcote Parkinson, in the well-known law which bears his name, examined the effort devoted to activities which are time-constrained. Law Number VI of the present monograph is a reciprocal to Parkinson's proposition, and considers the case wherein the *work* to be performed is constrained. Parkinson's Law pointed out, in essence, that work expands to fit the time prescribed. In contradistinction:

VI: In a noncompetitive process, time expands to fit the work prescribed.

The Impossible Only Takes a Little Longer

Law Number VII explains why one professional football coach, after having been given an unlimited budget by the club's owner, was accused before the season had begun of having overspent it.

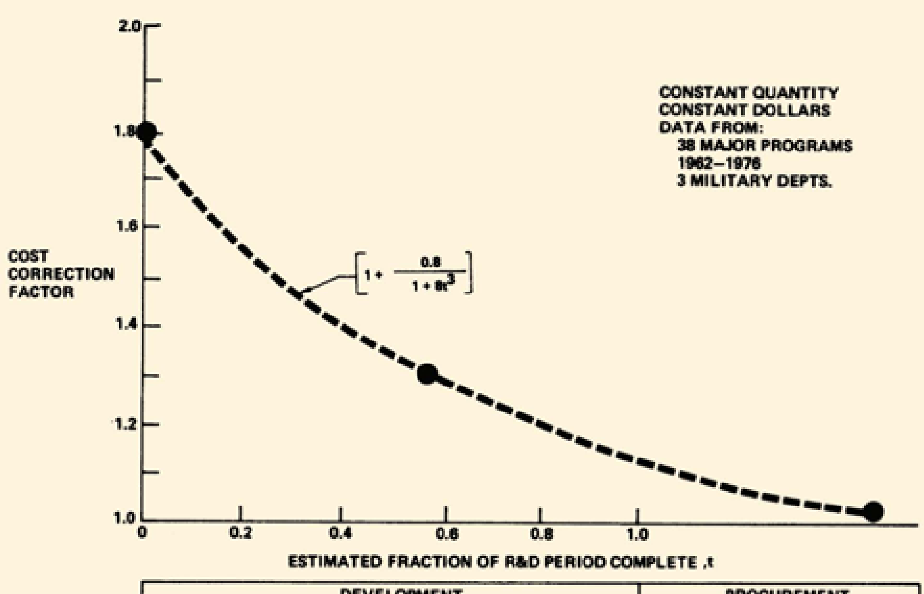
Two types of uncertainty plague most major programs: known-unknowns and unknown-unknowns. The known-unknowns, such as the composition of the moon's surface at the exact location of the first Apollo landing, can be accommodated and a program planned which hedges against their consequences. The second category, the unknown-unknowns, cannot be specifically identified in advance, but their existence can be predicted with every bit as much confidence as insurance companies place in actuarial statistics. An example of the latter category of unknown is the lightning that struck Apollo XII shortly after its launch on the way to the moon.

Somehow, in every major program, "lightning" strikes *somewhere*. It cannot be predicted *where* it will strike, only that it *will* strike. But, unfortunately, the budgeting system used in defense planning has not, at least until recently, permitted the recognition of such contingencies or the provision of lightning rods. This was in part due to the vulnerability of so-called management reserves to congressional budget cutting, and partly due to optimistic bids engendered in a cost-reimbursable competitive contract award environment.

Although there are available many more sophisticated ways of predicting program costs were one in fact to *use* them, the cost-estimating correction factor presented in Figure 9 would, in the aggregate, have eliminated overruns on defense programs during the recent decade had it been available and applied. It should be noted that when Figure 9 is in fact applied, the decision maker will undoubtedly have been misinformed as to what fraction of the program is actually complete. This distortion has already been compensated for in Figure 9 using Law Number IV.

A word of caution is, of course, in order with respect to the delegation of authority for the management of the contingency funds thus determined, lest

FIGURE 9
Predicting Program Cost (R&D Plus Procurement)



Parkinson's Law exert itself and costs thereby rise to meet the accessible funds. Thus we have:

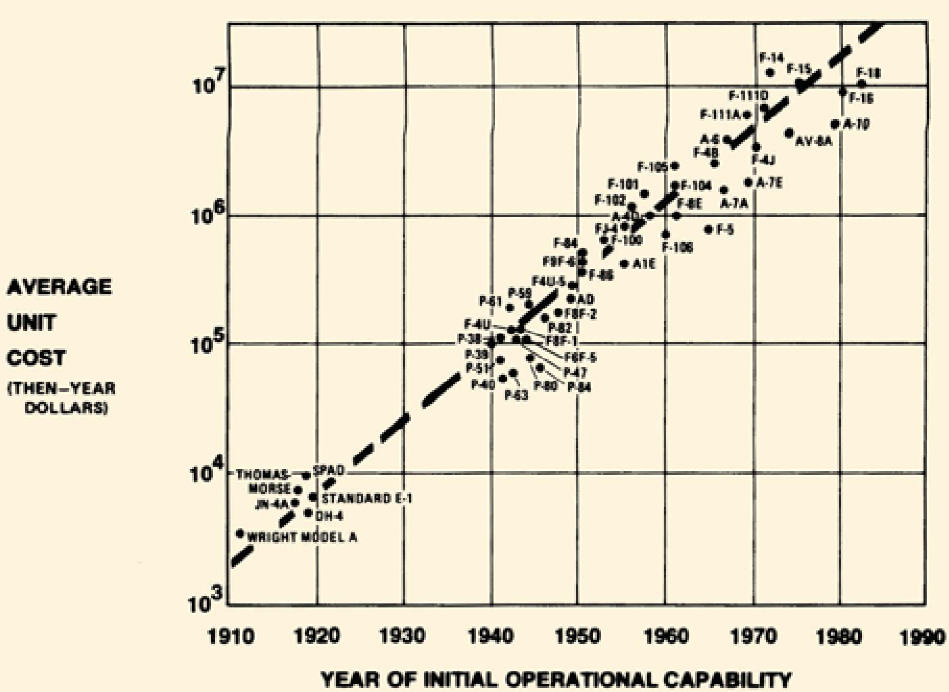
VII: In order to better the record of some program cost estimators of the past few decades, it will be necessary to work twice as hard; to be twice as smart; and to recognize unknown-unknowns. Fortunately, this is not difficult.

The High Cost of Buying

Law Number VIII addresses the prospect that warfare is pricing itself out of existence.

It can be shown that the unit cost of military equipment, as with much other high technology equipment, is increasing at an exponential rate. Figure 10 shows, for example, the historical trend of rising unit cost in the case of tactical aircraft.

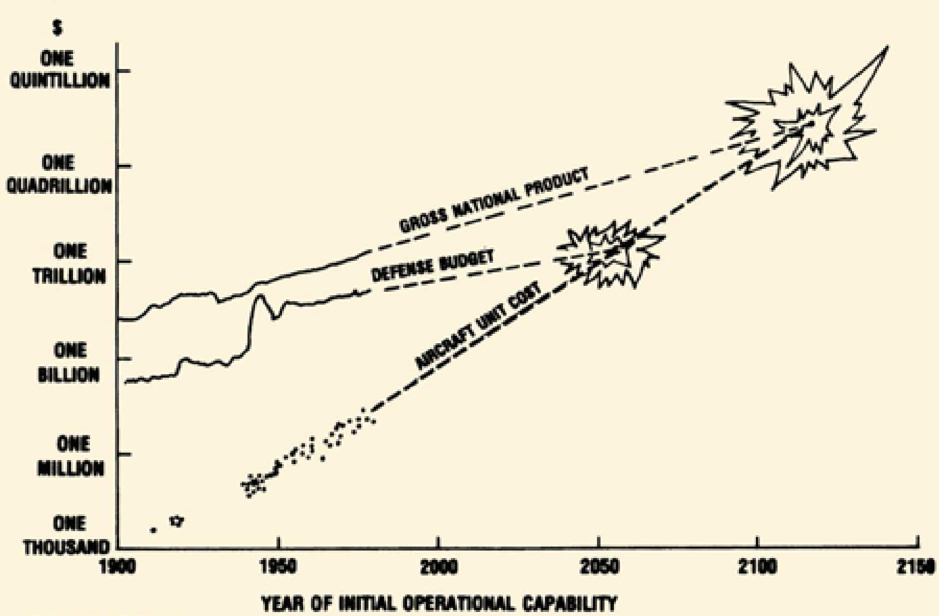
FIGURE 10
Trend of Increasing Cost of Tactical Aircraft



From the days of the Wright Brothers' airplane to the days of modern high performance fighter aircraft, the cost of an individual aircraft has invariably grown by a factor of four every 10 years. This rate of growth seems to be an inherent characteristic of such systems, with the unit cost being most closely correlated with the passage of time rather than with changes in speed, weight, or other technical parameters. The same inexorable trend can be shown to apply to commercial aircraft, bombers, helicopters, or even ships and tanks, although in the last two somewhat less technologically sophisticated instances, the rate of growth is a factor of *two* every 10 years. Seemingly then, the cost of high technology military hardware can be accurately explained in terms of an increase by a factor of four during each sunspot cycle, independent of anything else!

The significance of this observation does not, however, lie in the mere fact that cost growth is, in itself, predictable. Rather, it lies in a *comparison* of the rate of growth of, say, aircraft unit cost with the rate of growth of other relevant parameters, e.g., the defense budget. This particular comparison is presented in Figure 11, wherein the identical data points shown in Figure 10 are reproduced,

FIGURE 11
Calvin Coolidge's Revenge



but to a smaller scale in order to facilitate extrapolation into the future. Objection might be raised as to the validity of any such extrapolation; however, it is noted that the above-mentioned trend has faithfully prevailed throughout the history of aviation, presumably making such extrapolation no more hazardous than that used in most other fields of economic forecasting.

When the trend curves for the national budget for defense and the unit cost of tactical aircraft are, in fact, extended forward in time, as shown in Figure 11, a rather significant event can be predicted for the not-too-distant future. Namely, the curves *intersect.* And they intersect within the lifetimes of people living today. This observation has led to the formulation of Augustine's Eighth Law:

VIII: In the year 2054, the entire defense budget will purchase just one tactical aircraft. This aircraft will have to be shared between the Air Force and Navy 3½ days each per week.

One can only imagine the difficulties that such an arrangement will entail. And it should be pointed out to those who take solace in challenging the validity of the above extrapolation of the defense budget, that, were a plot of the gross national product to have been used instead, the above-mentioned singular event would have been delayed a mere 60 years.

This particular law might, perhaps, more accurately be remembered as "Calvin Coolidge's Revenge" as a tribute to the prescience of that gentleman. It will, of course, be recalled that it was Calvin Coolidge who once asked, in a moment of budgetary frustration (which now can be quantitatively understood), "Why can't we buy just one aeroplane and let the aviators take *turns* flying it?"

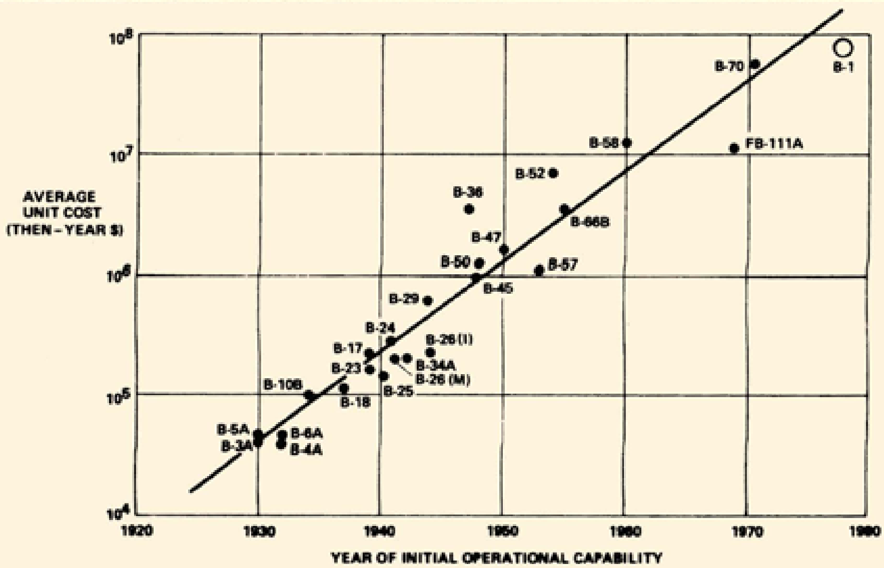
Turning to more recent events, Figure 12 shows the trend in unit cost of bomber aircraft, culminating in the B-1 phantom data point. For the sake of consistency, this curve can be referred to as "Jimmy Carter's Revenge."

On Doing Less with More

Law Number IX describes how one can make a silk purse out of a sow's ear—if, that is, one starts with a silk sow.

Although some types of systems are admittedly expensive, they clearly are also much more effective. Or are they? One such comparison can be made by examining the combat effectiveness of two classes of military systems having widely differing costs—guided missiles and guns. Figure 13 plots the military contribution of these two categories of systems during various major conflicts that have taken place since the advent of the missile age. In each of the conflicts considered, both types of systems were used fairly extensively, thereby providing a reasonably large data base. The combat impact of each category of system is measured in terms of the fraction of a given type of enemy materiel (airplanes, tanks, etc.) which was destroyed by missiles or guns, respectively. The cost of the

FIGURE 12
The Increasing Cost of Bomber Aircraft



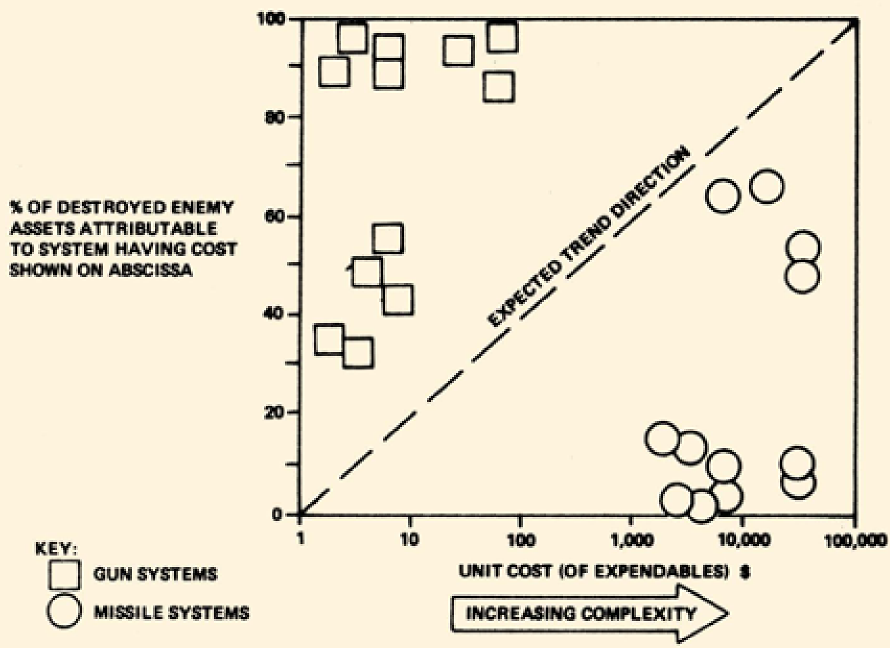
missile and gun systems is measured in terms of "expendables" only, which is, of course, an oversimplification, but which is at least partially justified on the basis that the launchers (aircraft, ships, or the gun tube itself) are reusable.

It might be presumed that the data points in such a comparison would aggregate along the dotted line shown in Figure 12; i.e., the more that one pays for a system, the more it contributes. Disappointingly, the actual data points do not behave according to such a trend at all. Instead, they cluster into two distinct groups as far from the expected line as possible. The data points representing missiles indicate that, at least to date, such systems have had relatively less impact on the outcome of battles than have the far less costly gun systems. This is presumably due in part to the increased susceptibility to countermeasures of the more sophisticated systems; but, more importantly, it is probably due to the fact that as equipment grows more costly it can be afforded in far lesser quantities, thereby sometimes offsetting the hoped-for improvement in individual-item performance.

The next law, thereby derived with a good deal of liberty from empirical evidence, can be stated:

IX: It is true that complex systems may be expensive, but they don't contribute much.

FIGURE 13
Impact of Various Systems in Combat



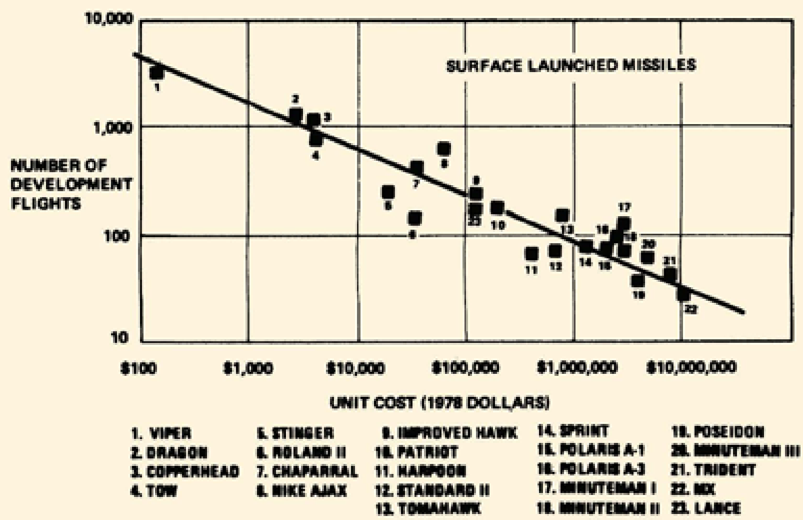
So Simple It Can't Be Trusted

Law Number X concerns the testing of new products and reflects a view expounded by one Casey Stengel, late of the New York Yankees: "I've had no experience with that sort of thing, and all of it has been bad."

Were one to examine the relationship between the amount of testing that is required of a newly developed item and the complexity of that item, it might not be unreasonable to expect that the more complex the item the more testing it requires. If, for example, a chart were made showing the number of flight tests of various missile systems against some measure of their complexity, the trend thereby observed would show a direct correlation, i.e., a line sloping upward to the right.

Not so. Figure 14 presents such a plot, based on the assumption that unit cost is a reasonable metric of "complexity." It is seen that the correlation is *inverse*, sloping *downward* to the right!

FIGURE 14
Relationship of Missile Complexity (Cost) and Number of Flight Tests Required



The amount of testing required thus seems to be more nearly explainable in terms of tradition than in terms of any technical rationale, with relatively simple unguided artillery projectiles somehow demanding thousands of test rounds whereas a new intercontinental ballistic missile needs only a few test flights to demonstrate its adequacy. The less complex the system, the more testing it then requires, a consequence of which forms the basis of Law Number X, the Augustine-McKinley Law:*

X: Truly simple systems are not feasible because they would require near-infinite testing.

As a corollary to the above law, it will be noted that when one knows the number of flight tests which are planned in a missile program, one may use Figure 13 to predict the *unit cost* of the item in question! This requires only a few man-seconds of labor and provides results that compare quite favorably in terms of accuracy with the official cost estimates for most programs during the past two decades.

*Charles H. McKinley, Technical Director, U.S. Army Missile Research and Development Command.

Going Nowhere, but Making Good Time

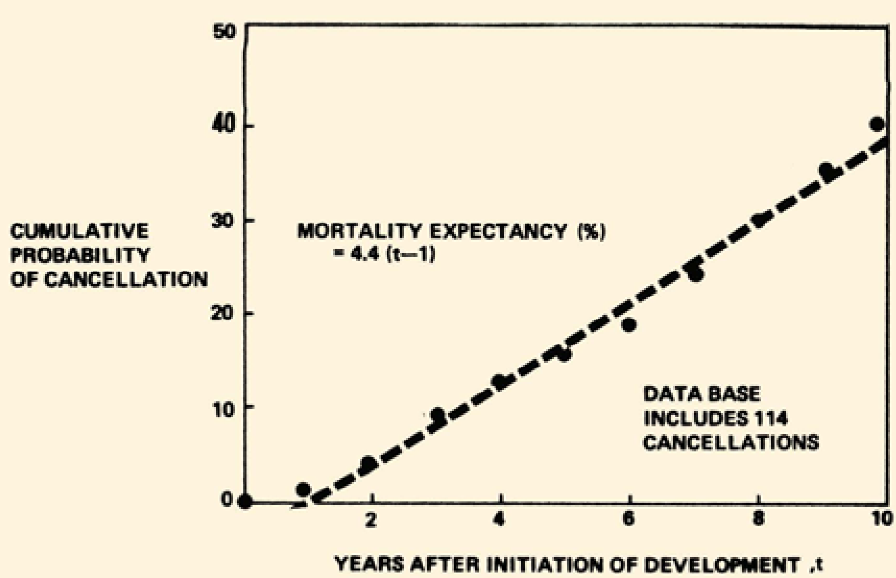
Law Number XI follows an observation made by a well-known college football coach: "The light at the end of the tunnel may be a freight train."

One consequence of the myriad of problems examined above is a relatively high mortality rate among development programs. This is a condition which, incidentally, is rarely reflected in a contractor's long-range sales plan, but which nonetheless is highly predictable in the aggregate.

The data presented in Figure 15 are derived from over 300 defense-related programs conducted in the past two decades. They reveal the probability that any given program will fail to survive the threats to its existence which arise prior to any given year in its life. It is seen that there is about a 4-percent probability of cancellation of a program each and every year except for the first year, sometimes referred to as the honeymoon period. This probability appears to be relatively independent of program age, presumably even for such aged endeavors as two current programs which soon will have been in development for 18 years.

XI: In terms of their chances of surviving, most *programs start out kind of slowly* and then sort of taper off.

FIGURE 15
Survival Expectancy of Development Programs

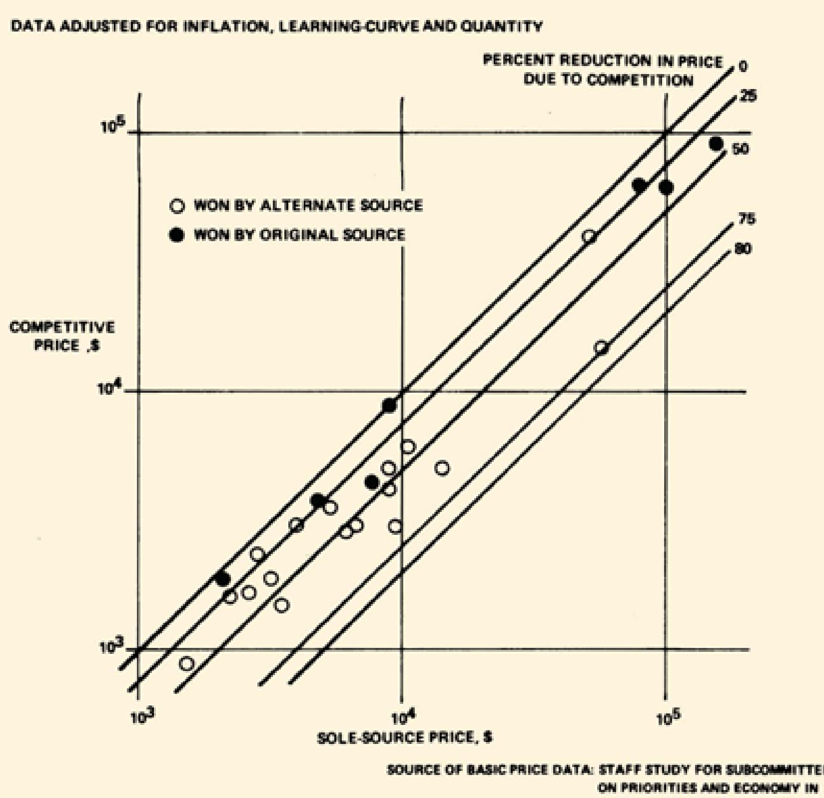


Do They Know Something We Don't?

Law Number XII examines a process similar to one once critically referred to by an executive of the Lockheed Aircraft Corporation as "You bet your company."

One of the most effective means of controlling cost while achieving good product performance is competition. But even competition must be applied carefully, or unwanted results occur. Consider, for example, the practice occasionally used in Department of Defense procurements of awarding the production contract for a newly developed system to whomever is the low bidder. This has the unquestioned impact of driving down the bid prices, and the disadvantage of sometimes

FIGURE 16
Effect of Competition on Unit Price



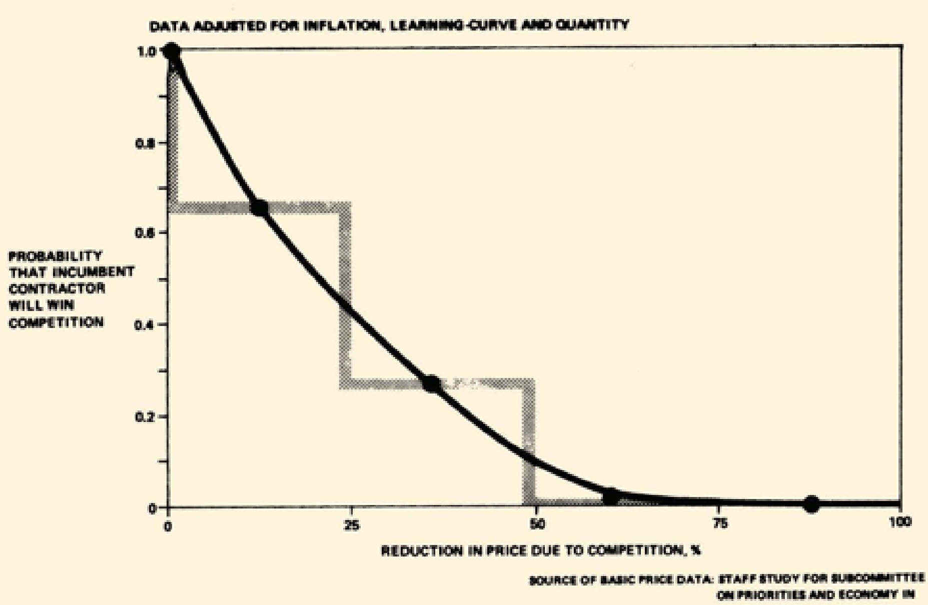
creating a producer who has no familiarity with the hard-earned lessons of how one actually goes about producing the product in question, lessons which were learned over many years of effort by the developer.

The data in Figure 16 verify that major bid price reductions are indeed obtained by competing a number of potential producers for an item developed by one specific contractor. (This figure does not, however, examine whether the winning bidder was ever able to actually manufacture a useful and reliable end product at the bid price—or any other price.)

Figure 17 examines the data in Figure 16 in a slightly different fashion. It indicates that the greater the winning price reduction relative to the developer's original price, the less likely is the developer of the item in question to be the winning bidder. It appears that an intimate knowledge of the task to be performed is somehow a handicap. Several interpretations are, of course, possible, one of which is expressed thusly (with apologies to Alexander Pope):

XII: Fools rush in where incumbents fear to bid.

FIGURE 17
The Ability of an Established Producer to Win a Breakout Competition



It was this law which an Army aviator, with whom the author once flew, had in mind when he added to the warning and caution stickers that traditionally abound in the cockpits of modern rotary-wing aircraft, this hand-lettered admonition: "Caution. This helicopter built by the lowest bidder."

The Budget Equation

Law Number XIII concerns the impact of the congressional appropriations process in defense system management.

In order to survive to completion, every government development program must maintain an extremely high single-skirmish-survival probability in its encounters with the various steps in the budget cycle. In the congressional approval process alone, a defense program's budget will be voted on at least 18 times a year, or a total of 144 times in the average program's lifetime. It does not seem to be possible to determine *a priori* the probability that any particular program will be funded or terminated by the Congress in any given year. It is, however, possible to predict with very good accuracy what the *overall* impact of the congressional approval process will be on the defense budget; that is, the result, in the aggregate, of the yearly congressional review process can be reduced to an equation.

Figure 18 displays the effect of congressional actions on the administration's defense budget requests in each year of the present decade. It is seen that a trend line can be quite accurately drawn which will predict the outcome of the congressional review process on the budget of any given military department, or on the Department of Defense as a whole. This would suggest that the Administration's efforts to gain approval of its budget requests have about the same impact year after year, independent of the political parties involved or the magnitude of the budget change requested, the latter even over quite large excursions.

These observations are summarized as follows:

XIII: In any given year, the Congress will appropriate for defense the amount of funding approved the prior year plus three-fourths of whatever change the administration requests, minus a 4-percent tax.

During the present decade, this law has applied with good accuracy over a ange of year-to-year changes in the requested funding level extending from minus 7 percent to plus 24 percent. This is shown in the above-mentioned figure.

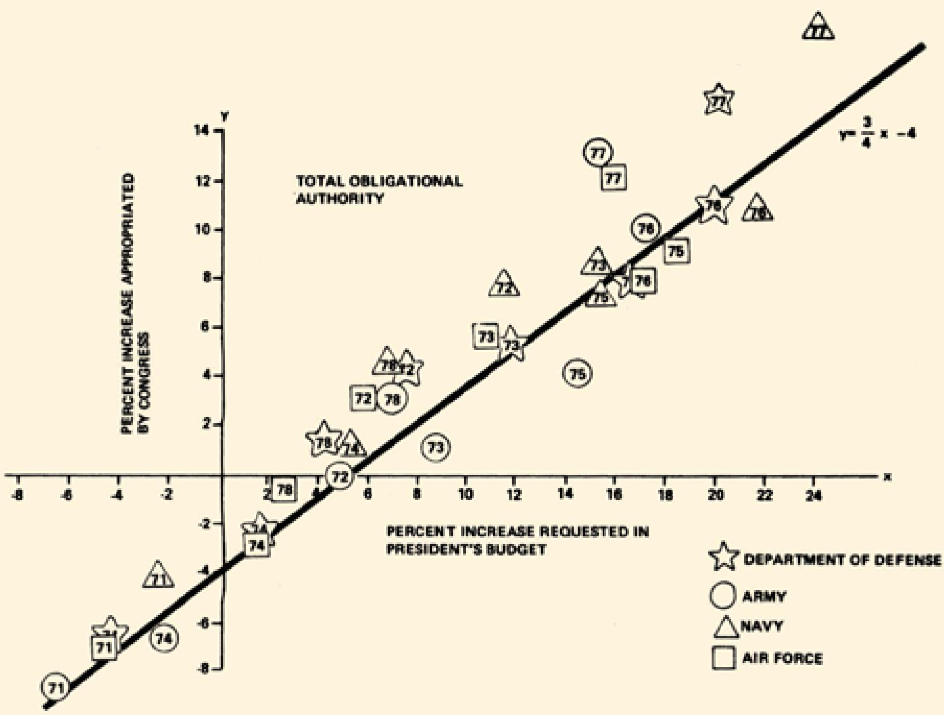
On Making a Precise Guess

Law Number XIV examines the parallel between management decision-making and Bismarck's observation about law-making. "Law," he said, "is like sausage: if you like it, you shouldn't watch it being made."

As reported to the Congress at the time development was to be initiated, the total program cost for the Harpoon missile program was said to be $1,031.8

FIGURE 18

Predicting Congressional Changes to the Defense Budget Request

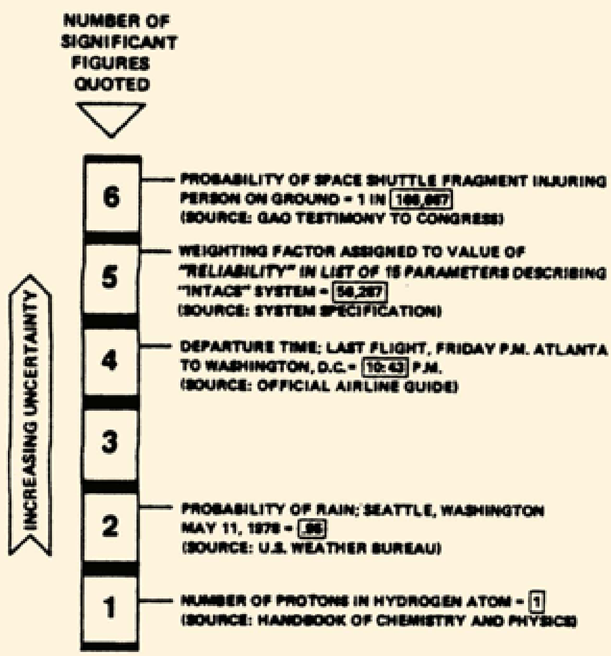


million. For the A-10 program, the corresponding cost was defined as $2,489.7 million—not $2,400 million; not even $2,489 million. Rather, the cost would be two thousand four hundred eighty-nine *point seven* million dollars.

This great degree of accuracy may perhaps be somewhat surprising to the uninitiated in view of the fact that history shows the *first* digit of past program cost estimates to have been in error, on the average, by about 100 percent! The General Accounting Office, in its most recent report on the topic, for example, has stated that for Department of Defense acquisition programs now underway, 67 percent are already overrun by more than 100 percent.

Nonetheless, by examining the data in Figure 19, it is possible to derive the logic which underlies the practice of quoting fundamentally dubious numbers with a very great degree of apparent accuracy. It is seen from the figure that there is indeed a relationship between the number of "significant figures" quoted and

FIGURE 19
Relationship of Implied Precision to Actual Precision



the true precision of the data at hand but this relationship is just the opposite of what one might expect. My next law, which is based on a substantive collection of data such as that presented in Figure 19, states:

XIV: The weaker the data available upon which to base one's position, the greater the accuracy which should be quoted in order to give that data an aura of authenticity.

A problem which has long been faced in applying Law Number XIV, however, has been what to do in those cases wherein the analyses from which the numbers were derived provide only rather discrete results, such as $1 billion, or 10 miles or 1 ton. The solution to this dilemma has been astutely observed by Lieutenant General Glenn A. Kent (USAF, Ret.) in his reviews of a large number of quantitative analyses. The solution consists simply of converting all data from the English system of measures into the metric system and back again!

A derivative of this technique accounts for such phenomenal accuracies as are identified in a bulletin recently carried by a U.S. wire service concerning a British citizen whose private airplane was reported to have missed crashing into the control tower at an airport in England "by less than 39.4 inches."

A related approach appears to have been used last year in testimony provided to the Congress by the General Accounting Office in which it was stated that the chances of a person on the ground being injured by a falling piece of a space shuttle launched in a northerly direction from Kennedy Space Center "are one in 166,667." It may or may not be coincidence that one change in 166,667 equates almost precisely to 6 divided into a million. But clearly, one would not feel nearly as safe knowing that the chances of being hit on the head by a falling piece of shuttle are about "half a dozen in a million" as he feels when the probability of that happening is a single chance in 166,667.

Still another approach underlies the fiscal year 1979 appropriation of $25.418 million for the Aegis program. Certainly, a great deal of detailed study must have been required to define the program's funding needs in such detail. But, alas, when scrutinized more closely it is found that the figure is the result of a compromise brought on by a dispute between the House and Senate whereby a lump sum of $11 million was simply patched on top of the original *request by the President*, which was for $14.418 million!

Actually, Sir Josiah Stamp, Her Majesty's Collector of Inland Revenue, was well on the track of Law Number XIV nearly a century ago, except that he applied it only to government and neglected its frequent use by industry, among others. Sir Stamp pointed out that: "The Government are [*sic*] extremely fond of amassing great quantities of statistics. *These are raised to the nth* degree, the cube roots are extracted, and the results are arranged into elaborate and impressive displays. What must be kept ever in mind, however, is that in every case, the figures are first put down by a village watchman, and he puts down anything he damn well pleases!"

Growing Like a Regulation

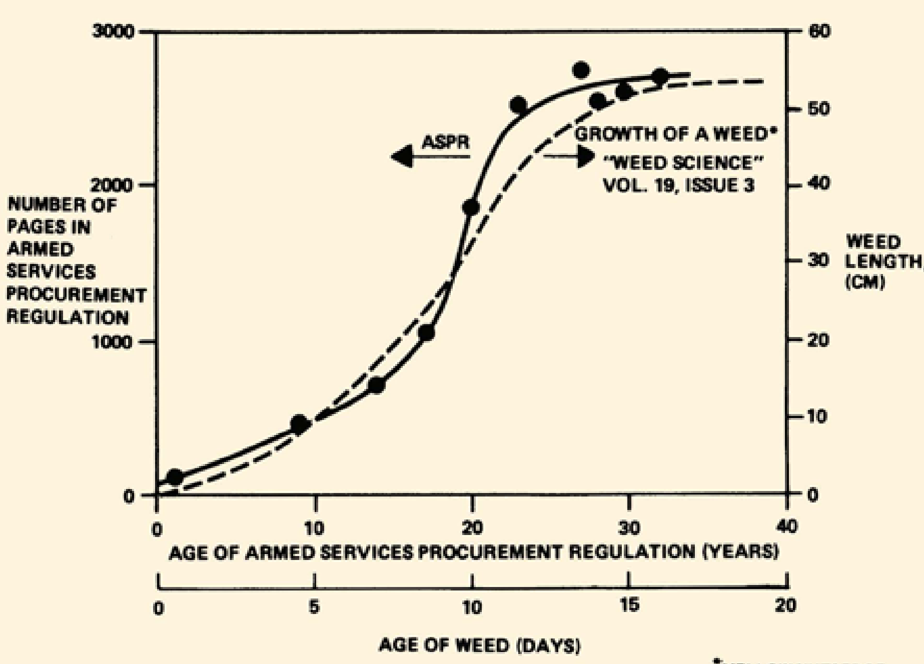
Law XV provides the mathematical foundation for Lamennais's apothegm, which states: "Centralization breeds apoplexy at the center and anemia at the extremities."

Large organizations, probably epitomized by federal governments, seem to be susceptible to the concept that regulations can become a substitute for management. Today, for example, the U.S. Government has imposed a set of 23,000 specifications on those who would sell to it a simple mousetrap. But, in spite of all the established rules, it is soon discovered that special cases occur, each requiring still further rules. And, of course, as new rules are added, none of the old rules is ever discarded; none, that is, until the entire management-by-regulation concept collapses of its own weight and a new cycle begins based on an altogether new set of regulations.

One particularly interesting but not atypical example of the growth of regulations is to be found in the Armed Services Procurement Regulation (ASPR) which governs procurement of everything used in the nation's defense, from aircraft carriers to the paper on which the ASPR itself is printed. Figure 20 shows the rate of growth of ASPR over its lifetime, and verifies that it indeed exhibits a behavior consistent with well established growth processes observed in nature. It is also noted that, based solely on its growth pattern, the ASPR appears to have reached its terminal phase—after which it can be expected to be replaced by a new set of policies.

The degree of improvement wrought by these growth trends, as they have prevailed over the years, is suggested in the case histories of two airplanes. When the Army Signal Corps purchased the development of an aircraft from the Wright Brothers, the entire contract (a fixed-price incentive type) comprised two pages. It was the result of a 40-day competition among 41 bidders, which was culminated in a 9-day evaluation period by the government. An award was made (without

FIGURE 20
Growth of a Regulatory System

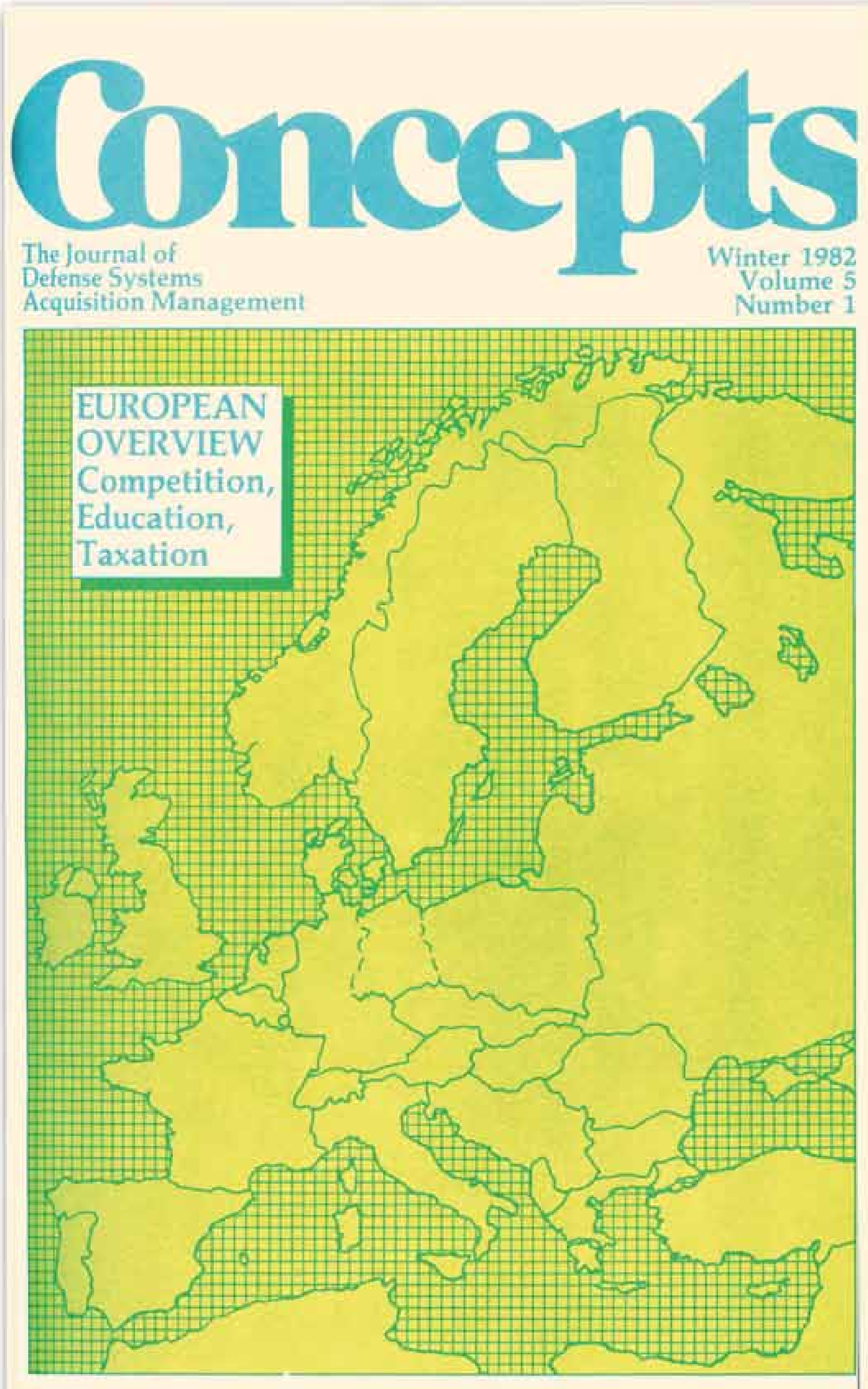


protest) and the aircraft flew successfully 6½ months later. The primitiveness of this management system contrasts sharply with the more sophisticated approach used today which, in the case of the giant C-5A transport, generated contractor proposals, the paper for which would have more than filled the C-5A itself. We are thus led to:

XV: Systems of regulations created as a management surrogate take on a life of their own and exhibit a growth history which closely parallels that of selected other living entities observed in nature.

Summary

Augustine's Laws, largely derived from empirical evidence, might be interpreted as suggesting that it is simply not possible to develop major systems. Such is not the case. This is demonstrated by the many successes achieved by many able and dedicated managers. What they do suggest is that the *unwary* manager will very likely fall victim to phenomena which are every bit as predictable, and every bit as invincible, as processes governed by the physical laws of nature. ||


Concepts
The Journal of
Defense Systems
Acquisition Management
Winter 1982
Volume 5
Number 1
EUROPEAN
OVERVIEW
Competition,
Education,
Taxation

Augustine's Laws and Major System Development Programs (Continued)

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Norman R. Augustine

(The Defense Systems Management College published the first installment of "Augustine's Laws and Major System Development Programs" (Laws I–XV) in the Spring 1979 issue of the Defense Systems Management Review *(Vol. 2, No. 2). Since then the author has added eight more "laws," which we are pleased to make available to* Concepts *readers. The American Institute of Aeronautics and Astronautics plans to publish, in the near future, the complete collection of 23 laws in hardbound form. This installment of "Augustine's Laws" takes up where the first left off—at Law XVI and Figure 21.*

The Manager of the Year

When the going gets tough, everyone leaves.

—Lynch's Law

Law Number XVI addresses the problem of management turnover and is premised on the possibility that most managers, when dealing in a variety of endeavors, think they know their capacity but simply pass out before reaching it.

Certainly, one of the greatest impediments to that fundamental precept of management referred to as "accountability" is the rapid turnover of individuals holding leadership positions. Government program managers in the acquisition process, for example, hold their jobs an average of only 30 months. Even this is a substantial improvement over the situation which existed just a few years ago, in 1965, when such managers retained their jobs an average of only 15 months. Over the last two decades the tenure of the secretaries of the military departments

Author's note: "Augustine's Laws," although sometimes written in a humorous vein to enhance readability and retentiveness, deal with real and serious matters. I offer them in a positive and constructive sense with the hope that they will, by drawing attention to problems and some of their potential solutions, assist in at least some small way toward the strengthening of our nation's defense capability.

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and the Secretary of Defense as a group has been no better, also averaging about 30 months. The consequences of this anonymity in responsibility once prompted an aggrieved Lyndon Johnson to remark, in response to a question by a reporter as to why he had not fired the individual who had scuttled one of the President's favorite programs: "Fire him? Hell, I can't even *find* him."

Could it be possible that so important a management tenent as leadership stability and accountability has been totally overlooked in managing our nation's defense affairs? No, there is reason for optimism. Consider the following newspaper article quoting senior Navy managers: "By constantly changing our . . . director every two or three years, we have destroyed continuity. If you had a million-and-a-half-dollar business, would you want to change bosses every three years for someone who didn't have any experience? Most directors come right from sea duty to this job, and it can take a full year to get to know the ropes. How many people in the Navy do you think know things like scheduling problems?"

Encouraging indeed: The problem *is* recognized. But is this an article from the pages of *The Wall Street Journal* discussing the management of an important new Navy fighter aircraft, or perhaps even a new shipbuilding program? Alas, the article is from the sports pages of *The Washington Post*, addressing the decision reached a few years ago to stop rotating individuals through the position of athletic director at the Naval Academy. At least we have our priorities in perspective.

Gilbert Fitzhugh, Chairman of the Blue Ribbon Defense Panel of the late 1960s, stated the situation in the following terms: "Everybody is somewhat responsible for everything, and nobody is completely responsible for anything." A two-star general once commented, in an outburst of candor in response to a question as to how he was going to work his program out of a seemingly untenable position into which it had descended: "Perhaps a miracle will happen, or else maybe I'll get transferred!"

This problem of personnel turbulence, troublesome in virtually all management situations, is particularly acute in the case of major research and development undertakings. Consider the fact that studies of the frequency of reference to technical articles held in libraries, and of the change of content of course catalogs in the scientific departments of universities, indicate that the half-life of many technologies is today only about 10 years.

Paraphrasing this inconsistency as once pointed out by the *Armed Forces Journal International*, we are attempting to develop major new systems with 10-year technology, 8-year programs, a 5-year plan, 3-year people, and 1-year dollars.

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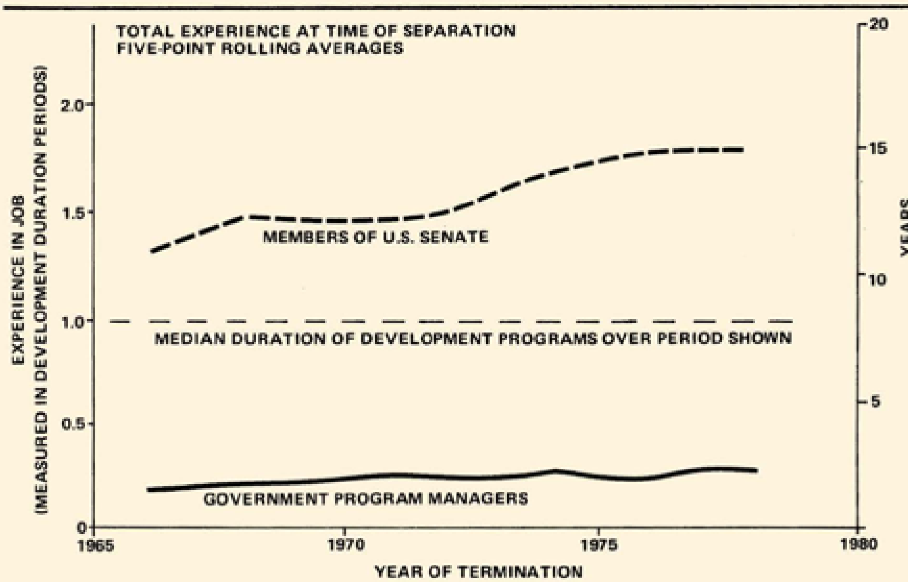
The evidence which underlies Law Number XVI is presented in Figure 21, wherein the longevity of program managers is compared with the (average) longevity of the programs they manage. As also shown in the figure, the people at the top of the legislative structure experience relatively *little* turnover. These numbers of the legislative branch not infrequently remind Defense witnesses testifying before R&D hearings that the congressmen and senators themselves know more about the history and underlying problems of the programs in question than does the parade of so-called experts who appear before them year after year with ever-greater enthusiasm and optimism. It is just this dichotomy, aggravated by the very length of the acquisition process, which in fact leads to the Law of Limited Liability:

XVI: The problem with the acquisition process is that by the time the people at the top are ready for the answer, the people at the bottom have forgotten the question.

FIGURE 21
Personnel Stability in Acquisition Process



Malice in Wonderland

> But Benjamin's mess was five times so much as any of theirs.
> —Book of Genesis

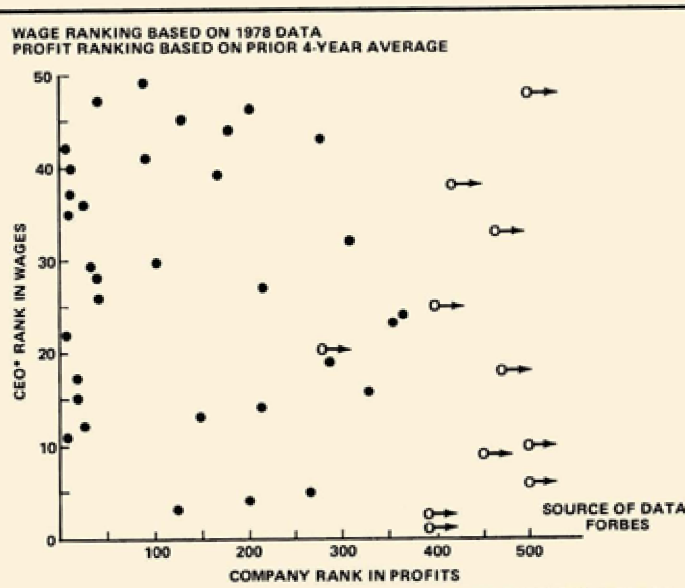
Law Number XVII examines the incentive system—and demonstrates that managers who produce exceptional results can expect the rewards they receive to be increased. Unless, of course, those rewards stay the same or go down.

"Call it what you will, incentives are the only way to make people work harder." The words of Andrew Carnegie? The creed of John D. Rockefeller? Or perhaps of Henry Ford? No, as it happens, these are the words of none other than that old capitalist Nikita Khruschev speaking on the benefits of the incentive program.

Having thus established the manner in which incentives are viewed in the Soviet Union, it is instructive to examine their use in the economic system extant in the United States, for which incentives form the very foundation—the "free-enterprise system."

Figure 22 displays the ranking of the 50 most profitable firms in the United

FIGURE 22
Relationship of Executive Wages to Company Performance



States in 1978 as compared with the rank according to pay received of the individuals who led those companies the prior 4 years.[1] The following law, known as the Augustine-Lemeshewsky[2] Law of Distributive Rewards, explains the evidence in Figure 22 (with apologies to P. K. Wrigley of baseball fame):

XVII: There are many highly successful organizations in the United States. There are also many highly paid executives. The policy is not to intermingle the two.

If a plot is made showing rankings according to return-on-equity, the lack of correlation exhibited is even more striking than that found in Figure 22 for absolute profits. The evidence seems to be incontrovertible.

Further, although one could never confuse the operation of the U.S. government with the free-enterprise system, it is still striking that an *overt* effort at demotivation has been practiced whereby the top five layers of management have all been fixed at the identical pay level due to the imposition of an apparently arbitrary wage ceiling.

The Half-Life of a Manager

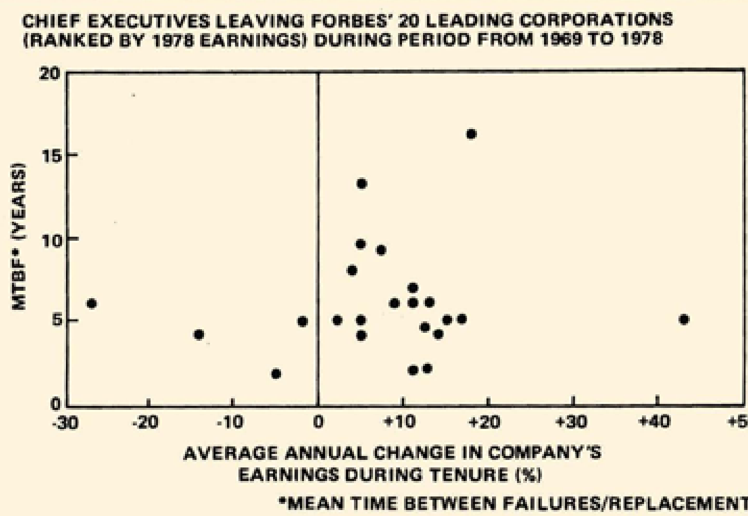
> We have a lot of players in their first year. Some of them are in their last year.
>
> —Bill Walsh, Coach, San Francisco 49ers

Law Number XVIII examines the viewpoint expressed by former Dallas Cowboy Guard Blaine Nye: "It's not whether you win or lose that counts," he says, "but who gets the blame." Will Rogers once pointed out, with respect to his business pursuits, "It is not the return on my investment that I am concerned about; it is the return *of* my investment." Perhaps within this philosophy lies the key to refute the rather disappointing thrust of the previous law.

Possibly the significant consideration with respect to successful managers is not what they *get* from their jobs, but rather that they get to *keep* their jobs. This possibility can be readily assessed using Figure 23, which displays the number of years the top executive in the 20 most profitable firms in the United States, in recent years, has been able to hold his job—as a function of the success achieved by that executive in increasing the company's profits. Unfortunately, the results are doubly disappointing. Not only do they fail to refute Law Number XVII, but worse yet, they call for still another law, the Law of Infinite Mortality:

1. For the occasional instances where the leadership changed during the period examined, the data for that company are not included in the figure.
2. Susan D. Lemeshewsky: Technical Operations Intern, Martin Marietta Aerospace.

FIGURE 23
Executive Survivability



XVIII: Executives who do not produce successful results can be expected to hold on to their jobs only about five years. On the other hand, those who do produce effective results can expect to hang on about half a decade.

It should be possible to fight this form of apathy; but so far it has not been possible to find anyone interested enough to do so. The conclusion of the above law seems to be true over a wide span of profit growth and even over severe profit "retrenchments," as they are gently referred to in stockholders' reports. The correlation coefficient between profit growth and the ability to retain one's job, on a scale where 0 is purely random and 1.0 represents perfect correlation, is calculated to be 0.1. The strongest correlation observed between longevity and any other parameter examined is found to be between the first letter in the name of the company and the first letter in the last name of the chief executive; as in "Ford, Henry II."

A median survival duration of a little over 5 years for top executives may seem rather short at first glance;[3] however, it is really quite good when compared

3. The data sample considered in Figure 23 contains a slight potential bias since the available evidence covers only a 10-year period. The impact of this is to have relatively little effect on the *median* longevity addressed herein; however, the overall (arithmetic) *average* longevity would perhaps increase to 7 or 8 years.

with many other professions such as, say, coaching football. Consider the case of the Washington Redskins coach, who, several years ago, was fired at half-time of the first exhibition game; or the situation that developed a few years later when the team had three head coaches in 24 hours. In fact, in pro football it is clearly a liability to be recognized for outstanding performance. Of the last 15 coaches to be honored by the Associated Press as coach of the year, 11 were fired within the next 12 months. As Bum Phillips, coach of the Houston Oilers, notes, "There's only two kinds of coaches, them that's been fired and them that's about to be fired." (Phillips has since been fired by Houston).

It would seem that to err may in fact be human, but to forgive is, by and large, against company policy. As John McKay, coach of the Tampa Bay Buccaneers points out, "They're paid to catch the ball." It can, of course, be asserted that many of the individuals included in the data base of Figure 23 retired or moved on to more important jobs. But it can be equally accurately asserted that many of these individuals were yet relatively young at the time of their departures and already enjoyed some of the best jobs in America.

Nonetheless, there is no need for discouragement, since the incentive system is, in spite of the above evidence, still alive and well: "People who show the best example in their work must receive greater material benefit"—according to a speech—before the Supreme Soviet—by the Premier—of the U.S.S.R. And right here at home it was recently pointed out that "the challenge for American capitalism in the '80s is to bring the entrepreneurial spirit back to America. Depressed areas especially need an enormous investment of capital. Individual entrepreneurship can create the new work ethic that is so desperately needed in America. To stimulate that ethic America needs creative financing . . . and I intend to work to create it."

So said Jerry Rubin, Yippie leader of the 1960s and a defendant in the Chicago Seven trial—speaking in the 1970s as a security analyst on Wall Street.

The Reliability of Unreliability

Adde Parvum Parvo Magnus Acervus Erit.[4]

—Ovid

The following law deals with the relationship between the reliability of complex hardware and that human tendency reflected in the World War II placebo: "We know of not a single instance wherein the enemy has successfully used camouflage against us." However, with respect to the matter of enhancing

4. "Add little to little and there will be a big pile." Quoted from *The Mythical Man Month* by Frederick P. Brooks, Jr.

reliability, we have in fact *viewed* the enemy; and, to once again quote that immortal possum, "he is us,"—but we seem unwilling to recognize this is the case.

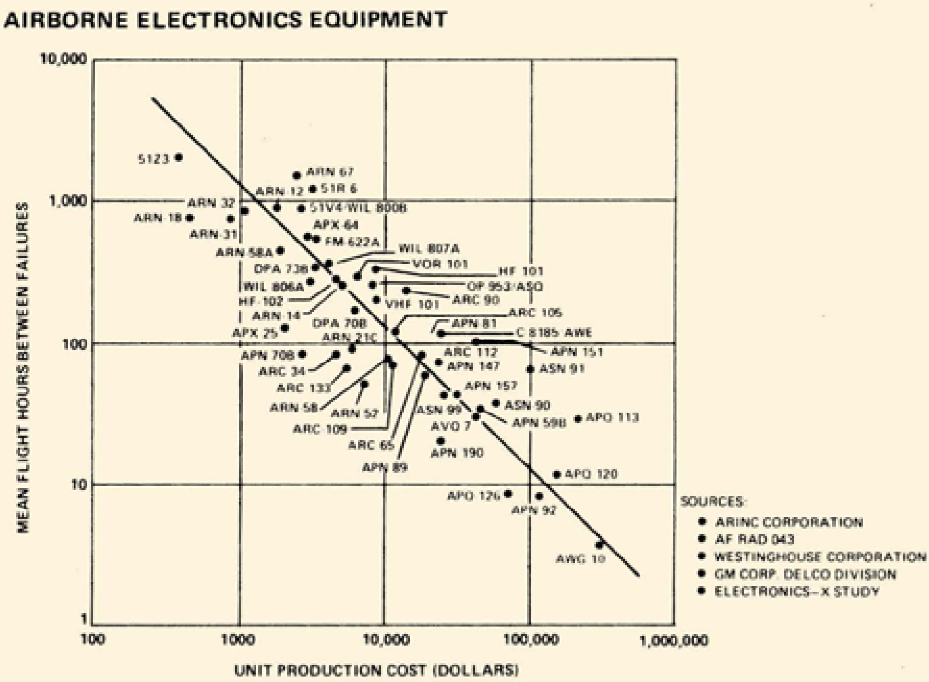
It does appear to be fundamental to the human race to believe that which one wants to believe rather than that which a logical examination of fact would reveal. George Santayana put it in the following terms: "All living souls welcome what they are ready to cope with; all else they ignore or pronounce to be monstrous and wrong . . . or deny to be possible." It would appear that Mark Twain may have been unduly generous toward humanity when he speculated, "I believe that our Heavenly Father invented man because He was disappointed in the monkey."

Consider the crucial matter of producing more reliable hardware; and, in particular, electronic hardware, which everyone knows comprises components whose individual reliabilities have been improving at a rate of about 15 to 20 percent per year for nearly two decades. Further, with size decreasing dramatically and the aggregate cost of integrated circuits consistently decreasing since 1963 along a 75 percent learning curve, it should be possible to achieve extraordinary system reliability through careful component selection and built-in redundancy—and thus to eliminate what has been one of the most troublesome problems for electronic equipment users for many years: unreliability.

In the words of Lieutenant General Orwin Talbott, "The longer a man is in a command position on the battlefield, the less enamored he is of the technological edge and the more obsessed he becomes with trying to make what he has work."

Now, if one were not privy to the anachronistic behavior of engineering and management activities as they have been dissected herein, one might in fact unwittingly conclude that as more and more money is spent on an item, its reliability would get progressively better and better. The initiated would never fall into such a logical trap and would recognize immediately that quite the opposite must be true. That this latter situation indeed prevails is verified in Figure 24, which exhibits field reliability data on a number of airborne electronic systems as collected during the Electronics-X study conducted under the aegis of the Institute for Defense Analyses. It is seen that the items examined range from relatively simple devices such as marker beacons and glide-slope indicators, to completely automated multichannel airborne intercept systems. The costs and reliability factors change with increases in inflation and technology—but the trend at any given time remains unwavering. Whatever the spectrum of equipment and techniques involved, the conclusion is unmistakable: As cost increases, reliability does not improve; rather, it worsens. Frank McKinney Hubbard (1868–1930 advises, "If at first you do succeed, quit trying." This is summarized in the Law of Undiminished Expectations:

FIGURE 24
Impact of Increasing Unit Cost on Field Reliability



XIX: It is very expensive to achieve high degrees of unreliability. It is not uncommon to increase the cost of an item by a factor of ten for each factor of ten degradation accomplished.

Dr. Eb Rechtin, President of The Aerospace Corporation, points out that such has been the pace of technological progress that by spending $250 million for an item, a mean time between failure of 30 seconds can be guaranteed. Correspondingly, one might suspect that a mean time to repair of 30 months could be suffered.

Although great care must, of course, be taken in interpreting the meaning of a "failure" (all failures are not created equal, nor do they have equal consequences), data released on the mean flight hours between failure for 12 different types of Navy and Air Force fighter and attack aircraft are illuminating. Nine of the 12 aircraft experienced a "failure" at least once every 30 minutes. Of those, five experienced failures every 15–20 minutes. This would seem to be conclusive proof of the correctness of those who have argued that the next strategic bomber must be supersonic rather than subsonic.

In any event, it can be understood why there are those who say that an airplane is merely a collection of spare parts flying in close formation.

It should be noted that the above law, regrettably, cannot be limited solely to airborne electronics. For example, even that most "ground-borne" item of military hardware, the tank, is a notorious offender. The M60A2, the first tank having an all-electric turret control system, contained 35,000 parts in the turret alone (and in the field performed for many years exactly like a tank with 35,000 parts in the turret alone). It was, in fact, just such a design which once caused Dr. John Foster, then the Director of Defense Research and Engineering, in an understandable moment of pique, to answer a question as to how one might best defeat a tank assault by saying, "Give them plenty of room to run around and they will all break down!" When considering the enormous logistical burden created by such problems of unreliability, some solace can perhaps be derived from the realization that if the Soviet Union's tanks have no better reliability and repair rates than ours, then with their huge inventory the Russians are stuck with more broken tanks at any given moment than we own altogether.

What, of course, is happening is that as component reliability improves, more components are crammed into each system to provide more and more capability—that is, more capability during those interludes wherein the system is not broken. A modern jetliner has about 4.5 million parts, including 100 miles of wiring. The Nike Hercules air defense system contained well over one million parts. But if a system has one million parts, each with a reliability of 99.9999 percent for performing some specified mission, the overall probability of the mission *failing* is over 60 percent. The foreman of a tank plant perceptively explained the solution in the following terms: "The part you engineers don't put on the machine ain't going to cause no trouble."

Thomas Paine summed it all up in the 1790s when he counseled, "The more simple anything is, the less liable it is to be disordered, and the easier repaired when disordered." Sadly, it has become commonplace to view high technology and simplicity as contradictory terms. The two are not, in fact if not in practice, antonyms. The problem is to use technology in a fashion which engenders simplicity. Who could argue, for example, that today's pocket calculators are less reliable than their 18,000-vacuum-tube predecessor, the ENIAC, which completely filled a room?

Law Number XIX, which states that expensive systems won't work, can be seen to pose a particularly serious dilemma to equipment designers when it is applied in conjunction with Law Number X, which already has noted that inexpensive systems are not possible (they require infinite testing). This all may be academic, however, since it has also been established (in Law Number VIII) that before long it will not be possible to afford any new systems anyway.

FYI

> We sure liberated the hell out of this place.
>
> —An American soldier, World War II

Law Number XX addresses the matter of engineers and managers destroying the English language while trumpeting the worth of their activities; or, as the saying in Brooklyn goes, "It was the loudest noise they ever seen."

Most major engineering activities depend on widespread public understanding for their funding or for their social acceptance, if not both. Yet, in spite of the many examples of contributions to mankind made possible through technology, the general public still harbors a considerable skepticism of the net benefit wrought by past technological advances. As a result, budgetary and environmental limitations abound, and support for basic research continues to erode in many quarters. The problem is exacerbated by the very language engineers and managers use to communicate their achievements, a language which appears to be formulated to assure that no information might be transmitted—either to the public or, frequently, among themselves.

A former Principal Deputy Under Secretary of Defense for Research and Engineering, Gerald Dinneen, met this problem head-on, pointing out that "we go to the Congress and tell them that our WWMCCS has got to have a BMEWS upgrade, our Fuzzy Sevens have to be replaced by PAVE PAWS, we want to keep our PARCS and DEW in operation, we have to harden the NEACP, and we have to improve our MEECN with more TACAMO and begin planning to replace AFSATCOM with Triple-S—and then we wonder why no one understands."

The extent of the problem faced by the uninitiated can be begin to be appreciated by considering the following excerpt from an Air Force document on the implementation of the new acquisition policy, A-109:

> —The HQ USAF/RD sends the draft MENS through SAF/ALR to OUSDRE for OSAF, OSD, DIA and OJCS staff, level comment.
> —The HQ USAF/RD OPR develops the for-coordination draft MENS and presents the MENS, comments and proposed solution approach to the HQ USAF RRG for corporate review in lieu of the underlying SON(s).

To the unwashed, this might convey a message something like:

—The blank blank/blank blank sends the draft blank through blank/blank to blank for blank, blank, blank, and blank staff-level comment.
—The blank blank/blank blank develops the for-coordination draft blank and presents the blank, comments and proposed solution approach to the blank blank blank for corporate review in lieu of the underlying blank(s).

Clearly, having drawn such a blank when dealing with the process of replacing ROCs (required operational capabilities) with MENS (mission element need statements), GORs (general operational requirements) and SONs (system operational needs), one can understand why there are those who have been able to conclude only that somehow SON of MENS must have been GOR'd by ROCS.

Of course, the liberal use of acronyms and other means of obfuscation does have the advantage of making sometimes pedestrian material appear rather erudite in that it becomes more difficult to comprehend. Who, for example, would pay a medical doctor $20 in exchange for his scribbling on a piece of paper "Take two aspirin"? Hence, the practice of writing prescriptions in Latin or, at the very least, using indecipherable handwriting.

A practitioner who, rather than admonishing "Take two aspirin," could prescribe "Take two acetylsalicylic acid" and, in addition, do so with poor penmanship could very likely qualify as a specialist and thereby command at least $40 for the services rendered.

As might be expected, the potential of uncommunicative communication has not gone unnoticed by the government and other large organizations. That most intimidating of all documents, the federal income tax Form 1040, is generously sprinkled with IRAs, HRs, IRSs, U.S.s, FICAs, RRTAs, R&RPs, EIs, EICs, ZIPs . . . and, ignominiously, something called "WINs."

This striving to impress is also evidenced above the entrances to public buildings, where the inscriptions, presumably for the edification of tourists, are of course offered in Latin. It thus may be that no one really knows what *E Pluribus Unum* really means . . . but no one can question that it is impressive.

A few years ago when in the midst of the national anti-ballistic missile debate the name of the then-troubled Zeus missile was changed to Spartan, it was only a matter of hours until some knowing wag had posted a sign on a Pentagon bulletin board proclaiming: "Spartan: Special Political Advantages Realized Through Advanced Names." A few years later, the oft-analyzed but never-deployed advanced manned strategic aircraft, AMSA, became known among its much-suffering advocates as "America's Most Studied Aircraft."

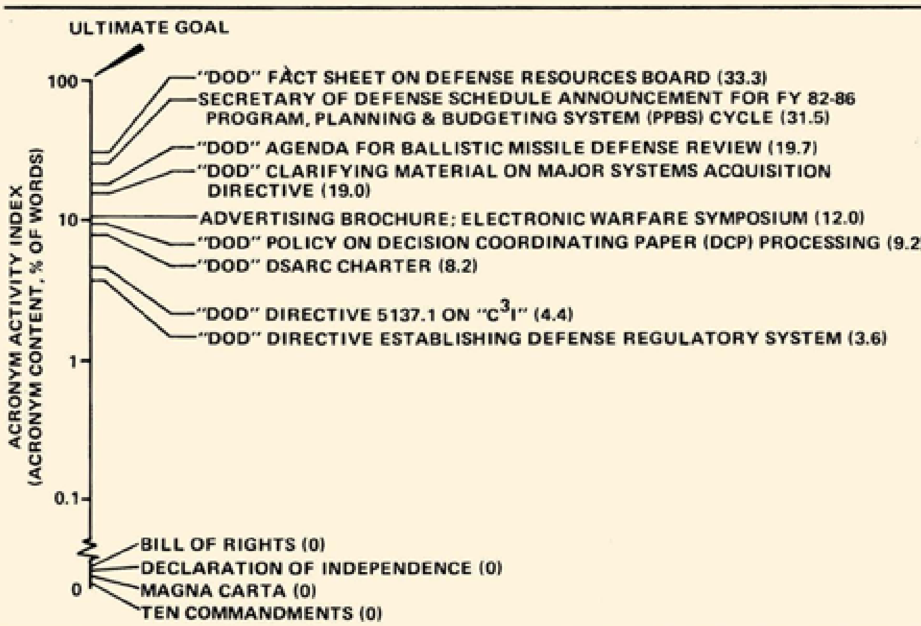
Similarly, at a security gate at Cape Kennedy on the approach to one of the launch pads is a sign which, among a number of cautions about explosives, flammable liquids, falling objects, high voltages, etc., conspicuously warns visitors that "POVs are prohibited." Now, this is, of course, cause for consternation among those who may wish to enter but are somehow not exactly certain whether they have a POV in their possession. It therefore can be with no inconsiderable relief that one learns that a POV is merely governmentese for "privately owned vehicle," i.e., presumably a shortened form for the word, "car." Correspondingly, a "range extension system," better known as an RES in guided bomb parlance, is, in less knowledgeable circles, merely referred to in its short form as a "wing"!

There are those individuals, both outside the government and inside, who are endowed with that special talent to take fairly straightforward concepts and, through suitable embellishment, make them quite nearly incomprehensible. The original lucid statement of the acquisition policy which David Packard, then Deputy Secretary of Defense, was to promulgate for the Department of Defense was written by himself and had an acronym content of only 0.2 percent of the words contained therein. However, by the time this statement was translated by acronymologists (so it could, presumably, be more readily understood) into the regulation which underpins much of the Defense Department's present acquisition policy (DODD 5000.1), acronyms comprised fully *10 times* the above fraction of all the words in the document. It seems doubtful, indeed, that Deputy Secretary Packard would ever recognize his policy in its new, improved form.

It is suggested that there are those who believe that a measurement of the percent of words in a particular work which takes the form of acronyms can be used to determine the implicit worth of that work. Clearly, the greater the number of acronyms the greater the intellectual value of the material since, obviously, the last thing anyone engaged in communicating would wish to do would be to deny a portion of the audience the message being conveyed. Thus, in view of their widespread use, acronyms must be concluded to be a valuable contributor to the worth of most material.

Figure 25 examines this premise and presents for a number of important acquisition documents the actual acronym use-factor, called the "acronym activity index" (AAI), measured in the fundamental unit called a "GLOP" (itself, not surprisingly, an acronym for "groups of letters for obfuscating points"). The success achieved in the bountiful use of acronyms in these documents is evident from the enviable ratings shown. These ratings are particularly creditable when contrasted with those of the more acronymically impoverished examples from other writings which are also included at the bottom of the scale. Clearly, communication in the

FIGURE 25
Use of Acronyms in Aiding Communication



material acquisition arena has risen to a very high plateau. In fact, a newly prepared government document has a list of 10,000 official abbreviations to be used in specifications alone. Approximately, the document is referred to as "DOD STD-12."

Law Number XX, the Comprehensive Law of Incomprehensibility, derived from evidence such as that just discussed, can be stated:

> **XX: Profound concepts are often characterized by their difficulty of being understood; therefore, persons unfamiliar with Greek or Latin should give intellectual depth to their ideas by utilizing acronyms to a degree more or less proportionate with the lack of sophistication of the ideas being presented.**

There are still further advantages to acronymical "anonymity." For example, it may seem quite sensible for a radar designer to point out that HF and UHF are simply too low frequencies to be of much interest for target-tracking applications. However, to state that "high frequency and ultra-high frequency are too *low* frequencies to be of much interest for target-tracking applications" would suggest the speaker must be suffering from some form of semantic delirium. Such is the advantage of being obscure clearly.

The current trend toward ever-greater proliferation of acronyms does, however, introduce a spectre of danger: the potential advent of an *acronym gap*.

The Defense Marketing Survey has stated that in carrying out its services it has compiled a list of over one million acronyms which are in common usage in defense matters. These consist principally of "words" made up of five or fewer letters. Since the number of possible five-letter (or less) acronyms that can be formed with the English alphabet is no more than about 14 million, it can be seen that nearly 10 percent of all possible reasonable acronyms have already been used up. With the accelerating use of such nomenclature, the day when the creation of new systems will no longer be possible thus may not be too distant. This, of course, portends ill since the Soviet Union enjoys a position of inherent acronymical superiority over the United States owing to its possession of an alphabet containing 32 letters. Some form of accommodation with China and its enormous language population of 14,000 characters would therefore appear to be prudent.

Still another possible solution to the acronymical gap would, of course, be to adopt even longer and less pronounceable letter groupings—an arena in which the U.S. Navy has been in the forefront for some time. One necessarily wonders, however, the impact even today on an organization's or individual's self-esteem to be known as the NAVHLTHRSCHEN, the NAVDISTCOMDTS, COMNAVOCEANCOM, or the NAVMEDRSCHU. On the other hand, this identity might not appear all that unattractive to individuals assigned to such organizations as ARF, ARG, NEMISIS, DRAG, MORASS, or AWFL[5] (pronounced "awful"), but would represent a considerable come-down to the Chief of Naval Air Training, CNATRA, better known simply as "Sinatra."

Many acronyms do not mean what the inexperienced observer might suspect . . . ANTS, GNATS, DOG, FROG, COD, APE, RAT, BAT, RAM, and CLAM have nothing whatsoever to do with the animal kingdom or Noah's Ark. Rather, they stand for airborne night television system, general noise and tonal system, Development Objectives Guide, free-rocket over ground, carrier on-deck delivery, advanced production engineering, ram air turbine, ballistic aerial

5. Aerospace Recovery Facility, Amphibious Readiness Group, Naval Ship Missile System Engineering Center, (Nuclear) Design Review and Approval Group, Modern Ramjet System Synthesis, Air Force Weapons Laboratory.

target, reliability and maintainability, and chemical low altitude missile, respectively.[6]

In the evolution of an acronym, letter combinations which defy pronunciation are simply reconfigured. Thus, National Emergency Airborne Command Post, NEACP, becomes the "Knee Cap"; the Combat Developments Objective Guide becomes the "Sea Dog"; the Nuclear Weapons Development Guide becomes the "New Dog"; the airborne laser illuminator, ranger, and tracking system becomes "Alley Rats"; and the radar target scatterer becomes the "Rat Scat."

The next anthropological stage in the development of an acronym takes place when verbal representations of a set of letters are converted back into a written form, a stage in which, inexplicably, the resulting acronym is often totally different from the one which started out! Thus, the fixed special surveillance (radar) known as the FSS-7 becomes, when rewritten, the "Fuzzy Seven." Or the electrical unit, the Pico-Farad, is abbreviated PF, which, after phonetic transliteration, is itself often de-breviated "Puff." The ultimate state of maturity of an acronym occurs when it is finally written in lower case and everyone forgets that it is in fact an acronym, such as "radar" and "laser."

Actually, those working on aerospace and other national security matters can make no particular claim to superiority in the acronymical arena. Regulators in all areas have excelled in the exploration of this powerful means of increasing confusion among the masses. Consider the world of federal finance, where the unpronounceable "FNMA" simply becomes a Fannie Mae—closely related, it is said, to a Freddie Mac. Still other mortgage instruments closely parallel in terminology some of the expressions already discussed pertaining to defense matters, such as SAMs, RAMs, FLIPs, and ARMs. Most ominous in the world of mortgages is something called a GPAM, occasionally pronounced "Gyp 'em."

But amid all this confusion is to be found redeeming virtue: Countless numbers of Russian cryptanalysts must surely be fruitlessly engaged in trying to understand what American managers are talking about.[7] Consider, for example, the dilemma of a Russian cryptanalyst confronted with the task of reporting to his superior a passage dealing with topics such as the computer language: "Jules

6. The author experienced the type of problems which can arise from such double meanings on the very first day of a recent tour in the Pentagon. While faithfully carrying out an assigned appointment schedule on Capitol Hill in preparation for a forthcoming confirmation hearing, the author felt it rather inappropriate that typed after the name of several senators on his calendar was the notation "OLD SOB." It was only some time later that it was learned that "OLD SOB" can, in Washington, also mean "Old Senate Office Building." Nonetheless, the ambiguity, in several instances, lingers to this very day.

7. Just as are many American managers.

own version of the international algebraic language, seismic instrusion detection systems, clear air turbulence, multiple independently targetable re-entry vehicles, modular electronic warfare simulators, modular electro-optical warfare simulators, high altitude particle physics experiments, beacon-only bombing systems, Develpment Objectives Guides, surface-to-air missile (systems), battlefield area reconnaissance systems, weather observing and forecasting systems, hostile weapons locating systems, submarine anomaly detection, tactical air-defense computerized operational simulators, biological aerosol detection, automatic test equipment, anti-radiation missiles, tables of organization and equipment, mutual assured destruction, built-in test, inertial navigation, high altitude transmission experiment, and directional attack mines."

Such a report by a Soviet analyst might sound something like:

JOVIAL SIDS CAT, MIRV, MEWS, and MEOWS.
HAPPE BOBS DOG, SAM, BARCS, WOFS, AND HOWLS.
SAD SAMS TACOS, BAD MIRV ATE.
MIRVS ARM AND TOE, MAD SAM BIT IN HATE.
. . . DAM!

In summary, simply stated, it is sagacious to eschew obfuscation.

Costing Enough to be Useful

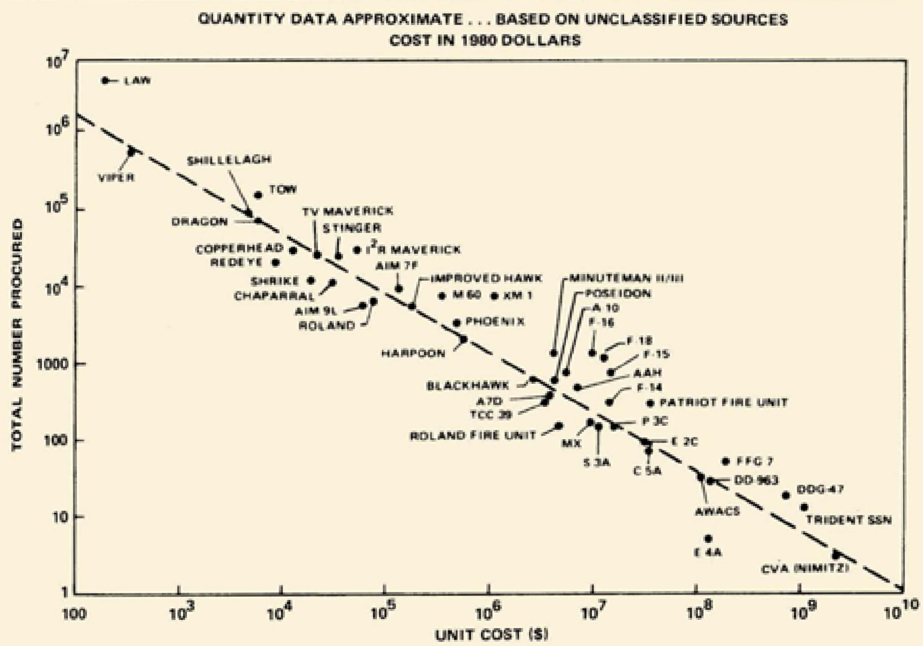
> Live within your income
> Even if you have to borrow to do it.
> —Josh Billings

Law Number XXI explains the empirically observed relationship between the cost of an item and the quantity of that item which is purchased; or, as tennis pro Ilie Nastase noted in explaining his failure to report the loss of his wife's credit card, "Whoever has it is spending less than she was."

Figure 26 shows the rather unexpected relationship which exists between the quantity of an item which is purchased and the cost per unit of that item. It is seen that most articles fall along a constant trend line which encompasses equipment spanning from the $100-per-copy LAW antitank rocket to the multibillion-dollar aircraft carrier *Nimitz*. Why this should be the case may help explain some underlying difficulties in the material acquisition process.

One obvious explanation is that the quantity of an item which can be afforded depends on the cost of the item, and the number procured is a simple consequence of that one fact. This seems to be a rather unsatisfactory interpretation, however, since it implies that there are no unique requirements for larger or smaller quantities of various types of equipment; one merely buys few of an item because it happens to be more costly or many because it happens to be less costly, independent of what the item may be intended to do or of the need for that item.

FIGURE 26
Cost-Quantity Trade-offs in Military Hardware



In this regard it is interesting to note that there exists a maximum acceptable unit price, $10^{10}/N^{1.2}$ for *any* individual item of equipment, and this price depends only on the quantity, N, of that item to be purchased. Once the quantity has been determined, the striking conclusion is that the cost of all items gravitates to this maximum. Additional capabilities somehow creep into the hardware until the unit cost approximates the above-mentioned value, which is known as the "threshold of tolerance."

Thus, any item of which only a few are needed can (and will) be allowed to take on additional features until the cost rises to the vicinity of the limit described. Bert Fowler, Vice President of the MITRE Corporation and former Deputy Director for Defense Research and Engineering, has pointed out that for some reason a mess table on a nuclear submarine costs substantially more than a mess table on a conventional submarine. Similarly, a clock in a Mercedes Benz costs a great deal more than a clock in a Volkswagen. So it goes with each component until the capability and cost of the entire system rise to the threshold of intolerance as described in the Law of Conservation of Input.

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In those early days, however, the pressure toward more capable and more costly designs was already at work. Professor Wood notes in passing that "the Curtis-Wright, Jr. airplane was designed to the following simple specifications, listed in order of importance: (1) low first cost, (2) safety, (3) appearance and performance. Professor Wood goes on to explain that "the actual first cost achieved in building this airplane (about $1,400 retail in 1930) was considered at the time to be exceptionally low, though the safety record was not quite so satisfactory, and the sacrifice of performance (cruising speed of about 65 mph) turned out to be so excessive that the airplane found little use as a means of transportation in competition with the automobile."

The seeds of increasing expectations were sown at an early time.

> **XXI: The features incorporated into any given system will continue to increase until the unit cost of the system in dollars approximates the Threshold of Intolerance, which is defined as $10^{10}/N^{1.2}$, where N is the quantity of the item which is to be purchased.**

This trend toward higher cost is, of course, exacerbated by the fact that the exponent in the denominator above is greater than unity. This means that the high unit cost which is acceptable for low-quantity items more than offsets the volume impact of high-quantity items—so that a contractor does slightly more business by dealing in high-cost/low-volume materiel. Similarly, program managers of high-unit-cost items will be able to enjoy the status of directing larger overall enterprises than their counterparts dealing in more economical systems, albeit procured in larger volume.

On the other hand, an approximation to Law XXI is that the quantity of an item procured multiplied by its unit cost always equals 10^{10} dollars. This provides a convenient method of determining the total procurement quantity for most programs.

Over the years others have studied various effects related to the one noted herein. Al Flax, President of the Institute for Defense Analyses and former Assistant Secretary of the Air Force, has pointed out one such interesting investigation described in the 1939 edition of *Airplane Design*. In that book, K. D. Wood addressed the relationship between the quantity of various types of aircraft which were purchased and the price of those aircraft. A principal difference in the observations of Professor Wood and the present data is, sadly, that the most expensive aircraft in the former study cost less than $5,000!

All Started by a Spark

Nearly all men die of their remedies, and not of their illnesses.
—Moliere

General of the Army Omar N. Bradley often and with his usual perceptivity quoted the old Signal Corps maxim that Congress makes a general, but only communications can make him a commander. In our zeal to emulate this truism, however, we have somehow managed to place ourselves in so extreme a position that it has sometimes been suggested that the side that wins the next war will be the one with the last antenna standing. As Bob Everett, President of the MITRE Corporation, has warned us with no inconsiderable amount of concern, there are those who would have us believe:

The American Soldier,
His strength is as the strength of ten,
'Cause he has LSI.

LSI, large-scale integration of electronic circuitry, is indeed important. But one suspects such intangibles as courage, motivation, and initiative may still be worth more than their weight in silicon.

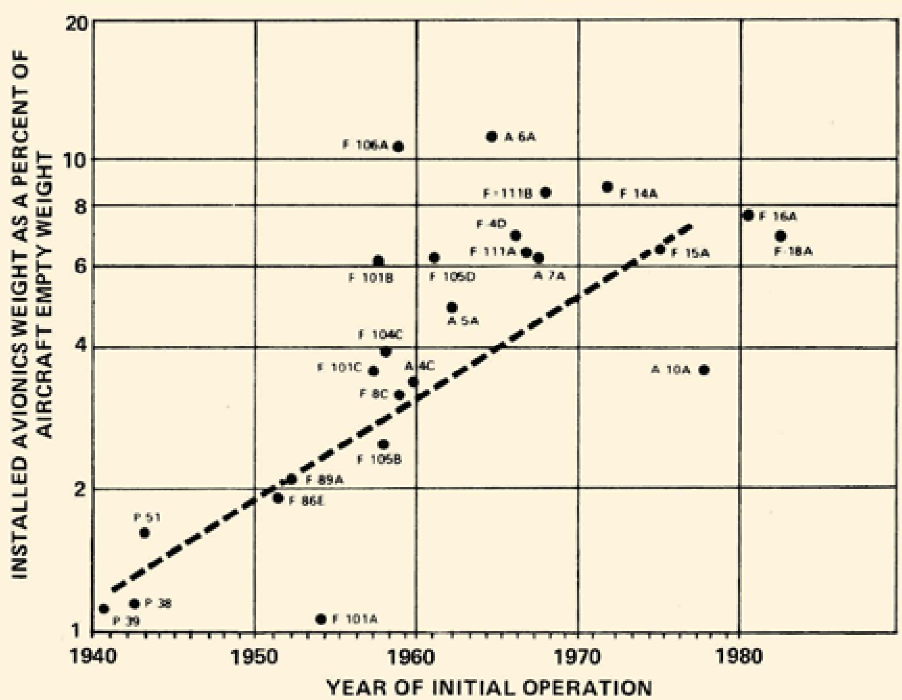
Nonetheless, *The Washington Star* reported that "if past wars were won or lost in places like the playing fields of Eton, future wars will be won or lost on computer terminals." The magnitude of the computer explosion has been illustrated in a recent session at M.I.T. where Michael Dertavzos noted that in the next few decades it will be feasible to store the world's knowledge in a computer for about half a billion dollars per LOC. But, in this case, an "LOC" is not the pedestrian "line of code," but rather, is a "Library of Congress." Needless to say, this is a potential that cannot be overlooked, either.

Such viewpoints do point to a trend in the proliferation of electronics which would be either productive or counterproductive, depending on how they are harnessed. The notion of computers fighting one another is *already* a reality. Much has been written about giant data processors developing codes to protect the secrecy of messages while enemy computers simultaneously seek to decipher those codes. Or, on a smaller scale, there are today computers controlling countermeasures devices in electronic warfare operations and enemy computers managing the enemy's counter-countermeasures equipment, and friendly computrs assigning counter-counter-measures, and. . . .

Each application of electronics thus seemingly leads to still another in an almost endless chain, raising the danger that electronics may indeed dominate all equipment before it can itself be controlled. Giant computers are at work designing their own offspring—the ultimate in electronic perpetuation. The extent of this prolific trend is examined in Figure 27, which represents the fraction of military fighter/interceptor/attack aircraft weight attributed to electronics. It has been observed that airplanes are merely a form of truck in which to carry electrons around the sky. Further, the trend with time is, unfortunately, unmistakable. Extrapolating once again, undauntedly, certain characteristics of that sole airplane which was proved in a prior law (Law VIII) to exist a few decades from now can be derived. Namely, it will be made entirely of electronics.

As dubious as it may seem, in order to sustain the above well-established trend, airplanes will eventually have to be built using black boxes in place of pilots and shooting streams of electrons or photons; this since there will be no space available for either pilots or bullets. In this space-age airplane, travel beyond the atmosphere may even be possible; but since there will be no room for

FIGURE 27
Trends in Avionics Aboard Fighter/Attack Aircraft



conventional engines, some form of electrical propulsion will presumably be demanded to give the electron its due. This has, clearly, the makings of science fiction, but the trend toward ever-increasing electronic content of aircraft does seem to deserve a skeptical re-examination. The Law of Unrelenting Electrification unabashedly predicts that:

> **XXII: The contribution to aviation is so great that by the year 2015 there will be no further airplane crashes. Unfortunately, there will be no further takeoffs either: Avionics will then occupy 100 percent of every airplane's weight.**

Only now, with the establishment of this law, can it be explained what Lord Kelvin, who did so much to advance modern science, had in mind when he predicted more boldly than wisely that "aircraft flight is impossible!" All those snickers over the years can be seen to have been undeserved; he, like Calvin Coolidge, was ahead of his time. But the law stated herein would certainly indicate that it was also not his finest hour when he predicted, "Radio has no future!" There can be little question that, as the Chinese proverb states, "It is difficult to prophesize, especially about the future."

It is clear that when Law XXII is fully realized, there will be no space or weight remaining on combat airplanes to carry weapons with which to attack the target. But even this may not be altogether inappropriate. With the high cost of modern air-to-ground weapons, it may prove cheaper to simply innundate the enemy with the avionics pods that will be filling most of the stores-stations anyway.

A related circumstance actually occurred during World War I when the German Air Force, seeking to draw fire away from its bases, began constructing a false airstrip occupied only by wooden airplanes, wooden vehicles, and wooden buildings. Unable to draw the attention of the Royal Air Force, the Germans continued to expand and improve upon the deception until finally, having spent nearly as much money as would have been required to construct a legitimate air base, they abandoned the effort in frustration. The extent of frustration was not, however, to become evident until a few days later when a lone British aircraft flew down the main runway and dropped a single *wooden* bomb!

It may be that the trend toward filling all available space *within* an airplane with electronics will eventually necessitate a return to the early days of aviation when the electronics were actually trailed on a line *behind* the aircraft. According to the 1919 edition of *U.S. Army Aircraft Production Facts*, "airplane radio antenna for telegraph work consisted of about 300 feet of fine braided copper wire trailing below and behind the plane from a suitable reel and held in place by a lead weight of approximately 1¼ pounds attached to its end." Unfortunately, with today's emphasis on low-altitude military flying, it is doubtful that the environmental impact of such a concept would be acceptable. Even in 1919, the practicability of such a scheme suffered some doubt in that it was duly noted: "Mr. McCurdy, the pilot, had to pay so much attention to flying his machine that he could send only detached letters of the alphabet."

In fairness, it should be noted that, as pointed out by Dr. George Heilmeier, a former Director of the Defense Advanced Research Projects Agency and currently Vice President of Texas Instruments, "If the automotive industry had progressed during the last two decades at the same rate as the semiconductor industry, a Rolls Royce would today cost only three dollars, and there would be no parking problem because each automobile would be one-quarter inch on a side!"

But, at the same time, there remain those cynics of the role of electronics who would point to instances in the space program where had a human not been on board there would have been no one available to repair the failures encountered in the life-support system.

There are also those who might irreverently note that if it were not for the radar display screens in cockpits, there would be no place to affix all the caution and warning stickers. The rampant use of computers is such that there are now those who refer to an airplane and its associated engines as "peripherals."

This trend is nowhere better represented than in the case of the manned bomber. The World War II B-29 contained about 10,000 electronic component parts, the B-47 approximately 20,000, the B-52 50,000 and the B-58 nearly 100,000 . . . or a factor of two each generation. But this rate of growth has been eclipsed by the B-1, which is packed with microcircuits containing as many active elements on a single chip as were carried in an entire B-58. Dr. Allen Puckett, Chairman of the Board of Hughes Aircraft Company, comments—not too seriously—that "the real miracle of the Wright brothers flight was that they accomplished it without the use of any electronics at all." He explains, "The only electrical devices in the *Wright Flyer* were the magneto and the spark gap in each cylinder of the engine." Today, an International L-1011 contains $4 million of avionics, which was roughly the worth of a DC-7C some 20 years earlier. In fact, about $1 million in 1960 would have bought every microcircuit then in existence.

Not only have airplanes succumbed to the electrifying experience of embracing high technology, but so too have the missiles they shoot. The Phoenix missile, for example, contains 538,000 active circuit elements, contrasting markedly with its forebear of a dozen years earlier which suffered through its existence on a mere 118 active elements. Fortunately, great strides have been made in increasing the reliability of electronic circuitry; however, correspondingly great discipline must now be exercised not to negate this gain by the unbounded introduction of more and more circuits.

Bit by Bit

We look at it and do not see it.
—Lao-tzu, sixth century B.C.

This law addresses one of the most ethereal substances to challenge technical managers in many years, a substance that seemingly creeps into systems to an ever-increasing extent, even in instances wherein its very need may be in doubt. It is somewhat as Mark Twain has noted, "Banks will lend you money, if you can prove you don't need it."

Considerable strain can be seen to be building within the acquisition process as engineers and managers seek to produce useful products while complying with the plethora of laws that have come into existence, both natural and man-made. Indeed, laws, like regulations, seem to grow like weeds (See Law XV). Complicating the effort to comply with all the regulations is the often contradictory guidance given by official bodies, such as the various committees of Congress. In fact, in several recent instances the Congress has gone so far as to *legislate* the initial deployment dates for new systems as part of the Appropriations Act. In doing so the dates are *law*. It is not yet clear what the exact liability may be for managers of those programs should they fail to meet the prescribed dates—especially in instances where the Congress subsequently cut their budgets—but it *is* clear that this has not significantly reduced the stress within the acquisition process.

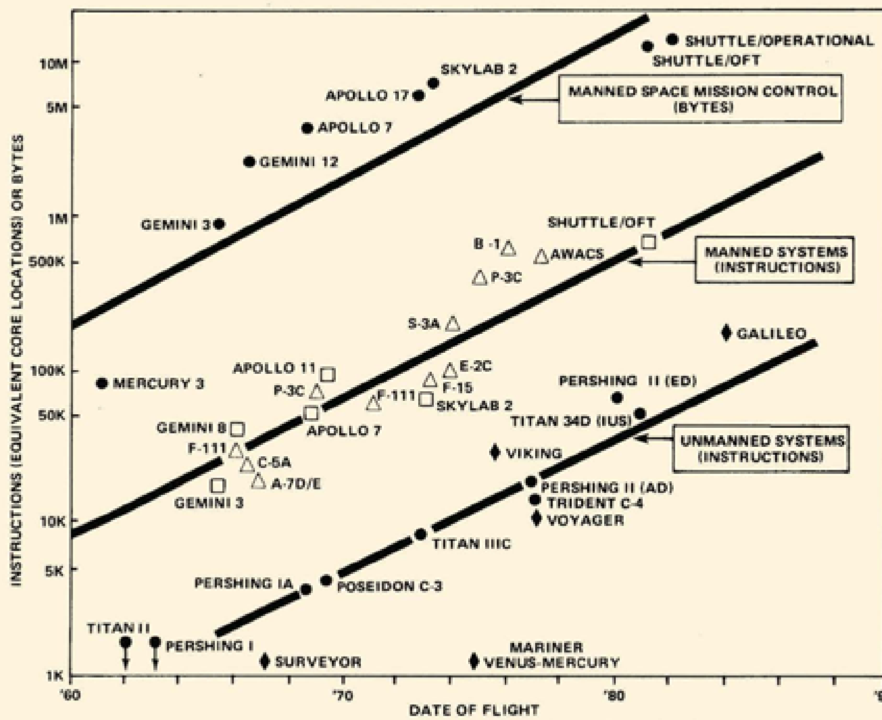
The dilemma faced by those involved in the acquisition process can be typified by the difficulty of complying with both Law Number VIII and the law discussed in the previous section, Law XXII, simultaneously. The first of these laws ordains that the cost of hardware (e.g., airplanes) increases rapidly with time. To comply with this stringent requirement in the time period when there will be no additional space or weight left in an airplane (since the entire volume will, according to Law XXII, be filled with electronics) places severe demands on a designer. Optimally, what is needed is something that can be added to airplanes and other systems which weighs nothing, yet is very costly, and violates none of the physical laws of the universe, such as the law of gravitation or the laws of thermodynamics.

This might appear to be an insurmountable challenge; however, as a result of the traditional ingenuity characteristic of system designers, it can be reported with confidence that such an ingredient has already been found.

It is called—software.

A principal property of software, the phantom of modern technology, can be seen in Figure 28, which illustrates the trend toward ever-increasing quantities of

FIGURE 28
Trends in Software Growth



SOURCE OF MANNED AIRCRAFT DATA: BARRY BOEHM

software in any given family of systems.[8]

There are, in fact, three separate growth modes evidenced by software. The first two of these are from generation-to-generation of new items of equipment (from an F-4 aircraft to an F-14) and from version-to-version of a given item of equipment (Titan I to Titan II to Titan III). The third growth mode, an internal growth mode, reflects the increase in quantity of software from the time the given

8. The groupings of the data shown in Figure 28 into the categories of unmanned and manned systems is interesting, but is most likely a figment of the rather modest data base available with which to treat this topic, although there can be little doubt of the reality of the growth trend within a given class.

job is initially scoped until it has actually been completed. This is often the most exasperating mode of software growth. It has been accurately stated that if you automate a mess, you get an automated mess. Figure 28 addresses the former two modes and suggests a growth rate on the order of a factor of 10 every 10 years.[9]

Law Number XXIII, the Law of the Piranha Principle, is derived from evidence such as that shown in Figure 28, with a strong degree of the encouragement from empirical evidence on the internal mode of growth, and is stated as follows:

XXIII: Software is like entropy. It is difficult to grasp, weighs nothing, and obeys the Second Law of Thermodynamics; i.e., it always increases.

Large-scale use of software can probably be traced back to the SAGE (semi-automatic ground environment) air defense system of the late 1950s, which was implemented using computers comprising 58,000 vacuum tubes and consuming 1.5 megawatts of power. The real-time operating program for this computer contained about 100,000 instructions (backed by support programs of 112 *million* instructions). A subsequent ballistic missile defense system, Safeguard, contained 2.2 million instructions, of which 735,000 were real time, illustrating, once again, the growth propensity inherent to software. There are those who would suggest that the contribution of such degrees of complexity will be excelled only by the projected advent of the WOM, the write-only-memory.

Various studies have been conducted which suggest that over the last 25 years the hardware/software portions of the cost of major systems are shifting from an initial 80/20 hardware/software ratio to a ratio approaching 20/80 in the decade ahead. It can be safely reported that the problems encountered in development programs have managed to stay abreast of this trend.

Actually, software exhibits many of the same properties as hardware. It is subject to human error (typically one error per 100 source lines of code), "reliability" problems, and high penalties for failure to discover problems early in the development effort. Barry Boehm of TRW has collected data which show the cost of correcting software errors at various points in a development activity relative to the cost incurred if the error is discovered in the coding phase. The cost is a factor of 5 greater when not discovered until the acceptance test phase and a factor of 15 greater when uncovered in the operational phase. It is left to Weinberg's Second Law to observe that if builders built buildings the way programmers write programs, then the first woodpecker that came along would destroy civilization!

9. The author is indebted to Stephen L. Copps for his assistance in collecting the data presented in Figure 28.

A classic example of the perversity of software was encountered in the Mariner program when on the Mariner 1 flight the lack of a single dash over a symbol in a little-used routine (the guidance module for failed doppler radar) resulted in a multimillion-dollar spacecraft striking out on its own to explore the distant universe instead of observing Venus as its human masters had intended. But if software is perverse, it is not without some redeeming virtues. The next Mariner flight was saved when the same set of equations (with the dash safely in place) managed to keep Mariner 2 on target in spite of an uncontrollable roll in the launch vehicle which caused loss of ground contact 75 miles before full lock was re-established.

But if the state-of-the-art in managing software development is in some respects primitive, the acronymical language used to cloud the art from those managers necessarily thrust onto the periphery of such activity has reached a high degree of maturity indeed. This language is laced with a veritable core-dump of bauds, bits, and bytes, MIPS, MOPS, and BOPS. In fact, the highest order of acronymical language thus far in use appears to have been created by software specialists working on command and control systems—thus effectively thwarting all those senior executives who may have had the audacity to think it was *their* role to command, or perhaps even to control. But the unquestioned greatest semantical contribution of the software art is the term originally coined to describe one million floating point operations but which can be seen herein to have much broader applicability in describing entire programs—or even entire groups of programs—i.e., the "megaflop." ||

Moving from BEST PRACTICES to STANDARD PRACTICES in Defense Acquisition

Alex Miller and Joshua L. Ray

Years of process improvement in defense acquisition have produced many isolated best practices that failed to become widespread standard practices. The authors' research identified six factors critical to seeing best practices adopted as standard practices. Both contextual and managerial in nature, these address the extent to which standardization is pulled, pushed, and practical. They organize the factors in a simple 2x3 framework, explain the nature of each factor, provide examples of each factor, and discuss each factor's implications for defense acquisition.

Keywords: *acquisitions; process improvement; best practices; standardization; innovation*

The military services have invested heavily in process improvement over the past several years, with decidedly mixed results in the field of acquisition (Browning & Sanders, 2012; Fox, 2011; Smith, 2003). While process improvement efforts yielded impressive gains, too often these improvements did not spread throughout the defense acquisition community, remaining isolated best practices rather than becoming widespread standard practices.

For example, in the authors' experience, several efforts to reduce acquisition cycle times produced impressive breakthroughs, often with cycle times reduced 40–60 percent. And yet, we see little evidence that the efforts producing these performance gains are becoming widespread standard practices.

Consider the perspective of members of a defense acquisition program team who had greatly reduced their source-selection time, allowing a badly needed system to be put under contract months earlier than expected. No one on the team could identify a single request to share ideas with other source-selection teams. Furthermore, members of the successful team were not confident that members of this team would apply lessons learned from their effort, even to their own future source-selection work!

This failure to leverage improved processes in pioneering programs and subsequently implement new work standards across similar programs, is greatly limiting the return on investment from process improvement in acquisition. Indeed, such failure can be viewed as a strong causal factor and contributing explanation as to why process improvement has failed to generate the overall performance gains desired by the acquisition community.

Background

In our research, we conducted in-depth field studies on organizations with notable successes and failures at standardizing best practices (Wicht & Crawley, 2012). In compliance with the security requirements of participating organizations, they will be referred to as Defense Contractor, Diversified Corporation, General Hospital, Heavy Equipment, Information Technology (IT) Manufacturer, Mutual Insurance, and Structural Fabrications.

Our field interviews and practical observations from time spent in these companies uncovered six determinants of process standardization that we have organized into a 3x2 matrix (Table 1). The matrix captures three broad types of forces we labeled as pull, practicalities, and push. "Pull" refers to motivations found within individuals (Harris & Lewis, 2012), while "push" forces are those brought to bear by factors outside the individual (Cash, Earl, & Morison, 2008; Edison & Murphy, 2012; Roper, 2011). "Practicalities" deal with the nature of the work and how readily it lends itself to standardization (Cash et al., 2008; Chatterjee, 2013; Thomke & von Hippel, 2002).

TABLE 1. SIX DETERMINANTS OF PROCESS STANDARDIZATION

		Three Types of Forces		
		Pull	**Practicalities**	**Push**
Two Origins of Forces	**Organizational Context**	1. Inherent Stakes	3. Replicability of Work	5. Organizational Alignment
	Managerial Actions	2. Making Advantages Visible	4. Implementing Standard Work	6. Driving Compliance

We found each of these forces could originate and grow out of organizational context and/or managerial actions. "Organizational context" refers to those factors "built into" the workplace or organization independent of any new action taken for the specific purpose of standardizing best practices (Chatterjee, 2013; Szajnfarber, Richards, & Weigel, 2011). As we will discuss, these are factors such as the inherent stakes of the work, the replicability of the work, and facets of the organization structure. "Managerial actions" refers to measures taken for the specific purpose of seeing best practices spread throughout the defense acquisition community to ultimately become standard practices (Garvin, Edmondson, & Gino, 2008; Kehoe, 2010; Pearson, 2002). These include making the advantages of standardization more visible, implementation of standard work, and greater emphasis on compliance.

Collectively, these six organizational and managerial forces have a tremendous impact on the extent to which organizations are able to standardize best practices. In the remainder of this article, we look at these forces in detail and consider their implications for defense acquisition.

Findings

Contextual Forces Creating Pull—Inherent Stakes

Several of the organizations we studied enjoyed considerable success in converting isolated best practices into widely deployed standard practices, but none of them found it easy. Even the most successful could identify areas within their organizations where the benefits of standardization and replication did not warrant the costs. Individuals referred to the "stakes" not being high enough to warrant the effort.

How high must the stakes be? In our research, firms committed to standardizing on best practices when it was literally a matter of life or death (Cash et al., 2008; Pearson, 2002). In other words, this happened when the health or life of individuals, or that of the organization as a whole, was seen as being at stake. A manager at Structural Fabrications (anonymous personal communication, June 2008) explained it this way:

> We have always been a production company. It is the heart of how we compete and the key to our success. Selling a commodity, we compete largely on cost and quality, and if we don't get production right, nothing else matters. There are also lots of ways people can be hurt in our production areas, so we are always working on improved safety. Put all of that together, and it just makes sense that we look hard for every opportunity to improve our production process. We're constantly learning from one another across shifts and across production areas. The stakes are just not as high in other parts of our business. For example, in business development you won't find the same effort to standardize processes.

Similarly, Defense Contractor identified standardization of its engineering processes as critical to its survival. The company had suffered through past problems with inconsistent engineering, and those inconsistencies were widely seen as the root cause in the company's loss of many millions of dollars and a damaged reputation in its industry. "Fixing engineering" came to be seen as essential to the firm's continued existence, and several dramatic steps were taken to ensure that best engineering processes were standardized across the firm. But there was little evidence of similar efforts anywhere else in the company.

World-class examples of standardization of best practices exist in many branches of the military. One merely has to look at where the stakes are a matter of life or death. In weapon systems operation, national security, and nuclear-based strategic defense, widespread efforts ensure that process improvements become new standard practices. Operations in these areas are subject to constant scrutiny with ongoing reviews looking for better ways of doing things. Once better ideas are identified, they are captured as standard work and spelled out in procedures, training, checklists, and inspections (Cash et al., 2008). It would be almost unthinkable not to take these measures because the stakes of failing to do so are so obviously high.

We have not observed the same phenomenon in defense acquisition. The situation in defense acquisition is similar to what we observed in Mutual Insurer, where we saw very little evidence of systematically sharing best practices across operating centers or sales districts, even though the work done in each Mutual Insurer location was virtually identical to that done elsewhere. The most common answer in response to questions about this lack of standardization was very revealing in that it highlighted the importance of perceived high stakes as a driver: "Standardization across organizational boundaries is hard. Why do it if we can get satisfactory performance working on our own?"

In summary, the perceived stakes inherent in defense acquisition are not sufficiently high to be an important driver of efforts to standardize and replicate processes. Note the emphasis on perceived stakes; the actual stakes are really quite high, suggesting the need for managers to make the stakes more visible (Edison & Murphy, 2012; Kehoe, 2010; Roper, 2011).

Managerial Forces Creating Pull—Making Advantages Visible

In this research, we found repeated examples of the importance of an organization recognizing the advantages that standardizing a best practice can offer, both to the organization and to the organization's workforce (Edison & Murphy, 2012; Harris & Lewis, 2012; Wicht & Crawley, 2012). Without managerial intervention to make payoffs more visible, there was often nothing to attract, or "pull," the workforce toward adopting best practices.

At IT Manufacturer, a struggling unit had come up with a radically different way of contracting for reverse logistics services. These were outsourced services involving either reselling, recycling, or scrapping returned computer equipment. The innovation was a clear winner, producing significant financial payoffs in its first application. In a nutshell, it expanded the conceptualization of reverse logistics to being a revenue generator rather than simply a cost center.

This shift in thinking and in contracting generated clear wins for both IT Manufacturer and its vendor. The vendor grew revenues and profits, and IT Manufacturer recognized higher revenues from new ways of reselling returned items. However, these gains were not at all visible to those doing the work in the two organizations involved. Instead, the vendor's workforce saw only that they were doing more work as they pursued new ways of generating revenue from returned items. Inside IT Manufacturer, the production division saw only that its charges for reverse logistics went up as the service provider was paid a higher processing fee per returned

> ***While leadership advocated greater use of the new contracting arrangement, employees on both sides saw no advantages and resisted, resulting in no movement toward spreading this better way of contracting to other parts of the organization.***

item. IT Manufacturer recorded increased revenues and profits, but the revenues were assigned to the sales division, and the increased profits accrued only at the firm level.

While leadership advocated greater use of the new contracting arrangement, employees on both sides saw no advantages and resisted, resulting in no movement toward spreading this better way of contracting to other parts of the organization. To remedy the situation, leaders at IT Manufacturer and its vendor agreed to participate in a highly visible ceremony at which they exchanged "Big Checks" documenting the financial gains from the first year of using the new contracting arrangement. Once employees saw the amounts on the checks and realized the impact of the new contracting, they became converts. Today, the new contracting arrangement is seen as a key competitive advantage for both IT Manufacturer and its vendor.

At Defense Contractor, engineers resisted the implementation of standardized engineering practices, arguing that it would restrict their creativity and ability to do good engineering. It took a concerted effort by leadership to show examples of how, in fact, by adhering to agreed-upon engineering practices, engineers' lives were simplified, and time was freed up for doing more and better engineering.

Note in the Defense Contractor example, the firm only benefitted from standardization after the individuals came to see it was in their personal best interest (Edison & Murphy, 2012; Wicht & Crawley, 2012). The benefits were not necessarily monetary, and we observed the same thing at Structural Fabrications, as explained in this quote from a senior operations leader in the firm (anonymous personal communication, June 2008):

> Management saw improvements in key performance metrics tracked by the company just as soon as we started rolling out the new production management process. The results were good enough to get managers to enforce adherence to the new processes for awhile. But as long as the guys on the line didn't see an advantage to themselves, the only way they adhered to the new procedures was by being forced to do so by their supervisors. Where the new process spread, it was because someone took the time to help the operators see their WIIFM—their "What's in It for Me?" It turned out there

> were plenty of advantages for individual workers—less rework, more predictable work schedules, safer workplaces, etc.—but leaders had to help the workforce see them. Once they did this, there was no turning back. Now the new process is locked in as the way we do things around here. But, where people never made the connection between the new process and what matters to them, implementation eventually became token and faded. Company ROI [Return on Investment] will only take you so far—eventually, you have to help people see what is in it for them. It is this one-two punch that gets the job done.

This one-two punch is seldom present in the defense acquisition community. Perhaps senior leadership is generally aware of the advantages of improved acquisition processes, but do members of specific program-management teams or functionals see personal advantages?

Often, they do not. For example, in a decade of work with military acquisition, we found few individuals who could articulate how they would personally benefit from reducing throughput time on a given program. As well, few could clearly show how they personally benefitted from best practices becoming standard. And very few individuals in defense acquisition felt their careers would be advanced because of their adoption of a best practice first developed elsewhere.

Contextual Practicalities—Replicability of Work

Some types of work and organizational structures lend themselves to replication of best practices more readily than do others (Cash et al., 2008; Chatterjee, 2013; Szajnfarber et al., 2011; Thomke & von Hippel, 2002).

Franchise restaurants are a classic example. When an individual Subway sandwich shop discovered that promoting "$5 Foot-Longs" generated tremendous volumes and improved profits, it was only a matter of weeks until 39,000 franchised stores followed suit. Consider the contextual practicalities making this possible. Each store offers virtually identical sandwiches prepared and sold in virtually identical ways, and all stores are connected with a strong and efficient communications network. These practical considerations make it relatively easy for a franchise operation such as Subway to spread a good idea across the organization quickly.

This should not imply that these practical contextual forces are sufficient in themselves to spread best practices. Mutual Insurance shares many of the characteristics inherent in a franchise; virtually identical products and procedures can be found across thousands of agents' offices and scores of operating centers. Yet, Mutual Insurance has failed to see best practices spread to become standard practices for reasons related to several of the other five forces in our model.

Within defense acquisition, we find very little standardization across processes. In this arena, emphasis is often placed on identifying differences between programs rather than stressing similarities. While literally thousands of pages prescribe acquisition procedures, many programs still find it essential to operate with virtually unlimited use of the so-called "county option" to create exceptions and new procedures. To an outsider, defense acquisition appears to be like Mutual Insurance in failing to capitalize on the similarities inherent across its varying operating units.

Still, it stands to reason that the closer products, users, and procedures are virtually identical across a large number of "franchise-like" units, the more likely processes can be standardized (Cash et al., 2008). For example, the military services have been able to standardize many administrative procedures related to flight operations, including training techniques, "hot wash" after-action reviews, and maintaining pilot currency. While every flight is different in its details, in many ways flights are similar, and a flight team's inventing its own operations process based on the argument of its need for a "county option" seems ludicrous. Where commonalities exist across acquisition programs, the same opportunities exist, but too many acquisition personnel are more interested in showing how programs differ than recognizing fundamental commonalities (cf. Pearson, 2002).

Managerial Practicalities—Implementing Standard Work

"Standard work" refers to the means by which an organization defines and documents its best practices to maintain dependable processes (Browning & Sanders, 2012; Smith, 2003). Standard work spells out the currently accepted best means of accomplishing a given task to the individual performing the work. Without standard work, individuals lack any practical means of implementing standardized processes.

In the organizations getting the most from standard work, managers invest heavily in its implementation. At Heavy Equipment, hundreds of formally designated "owners" are responsible for continuously improving their assigned processes. Owners are selected because of their experience and expertise with a given process and their demonstrated commitment to continuous improvement. Process ownership entails regularly meeting with those that carry out the process, with downstream users of the process output, and with those working in related processes. Out of these meetings, the process owners generate improvements that are captured in user-friendly source documents, training materials, and inspection standards. Efforts related to improving, documenting, and training on standard work often consume one-third of a process owner's time at Heavy Equipment.

> ***Process improvement efforts of the past decade have produced important pockets of standard work in defense acquisition, but these are not becoming standard work across the larger enterprise like they have in the best organizations we studied.***

At Defense Contractor, heavy emphasis is placed on standard work as it applies to engineering. Standard work was deployed at Defense Contractor in the early 2000s with the advent of computerized tools to support the capture and dispersal of standard work. Until then, small-scale attempts at improved engineering processes had occurred in pockets throughout the organization for many years. Eventually, a concerted corporate initiative to implement standard work provided the most benefit to the organization. Senior leadership not only directed personnel toward the use of standard work, they demanded it. The most senior leaders at Defense Contractor ordered their engineers to engage in the standard work by insisting: “Put your pencils down, and don’t continue until you create and use engineering standard work.” One employee recalled the sentiment and conversation (anonymous personal communication, June 2008) of that time as follows:

> We can’t operate like this anymore. This is a call to arms. We’re gonna stop, we’re gonna put people on reducing our cost of poor quality and understanding what’s driving that, and we’re not going to allow anybody to start designing until we get our standard work nailed down.

The results were dramatic; engineering issues, both trivial and more substantive, dropped from thousands a year to dozens a year. Today, senior leadership feels that engineering standard work is essential to the firm’s success.

Process improvement efforts of the past decade have produced important pockets of standard work in defense acquisition, but these are not becoming standard work across the larger enterprise like they have in the best organizations we studied. The opportunity is there for defense acquisition to take standard work to the next level and see isolated best practices become organizational standards.

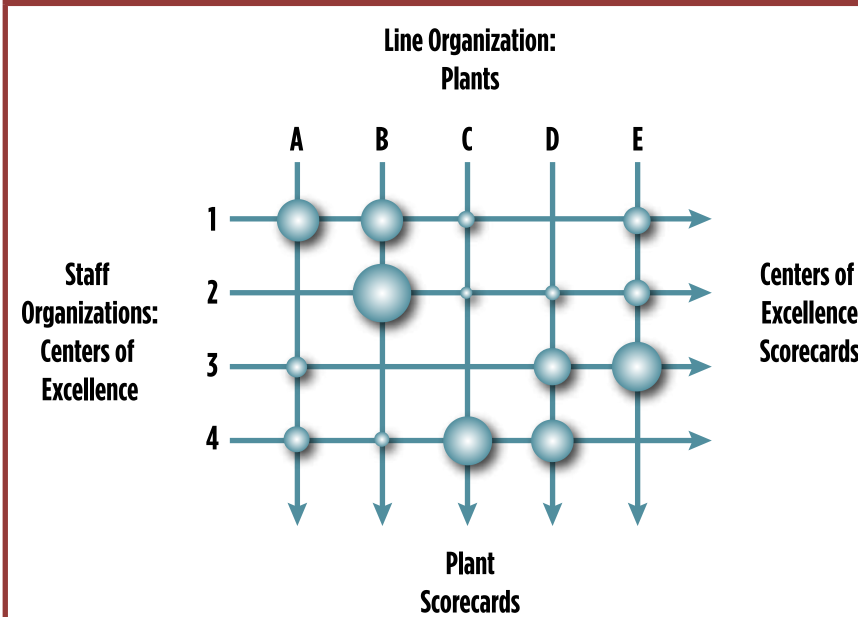
Contextual Forces Contributing to Push—Organizational Alignment

Of the organizations we studied, those most successful with standardization of best practices went to great lengths to “bake it in” to their larger strategy and structure (Cash et al., 2008; Chatterjee, 2013; Szajnfarber et al., 2011). Strategy, structure, and standardization were all consciously aligned and reinforced one another. One of the most powerful types of alignment we observed was that between line and staff organizations.

For example, at Structural Fabrications, production improvements were priorities, each backed up with a centralized, company-wide, staff-supported initiative. These included initiatives such as those to improve safety, reduce waste, increase employee engagement, etc. Staff groups variously described as "Centers of Excellence," "brain trusts," "corporate ninjas," or "subject matter experts" supported each corporate initiative. The primary role of these groups was to identify best practices and assist plants in deploying them.

These staff groups operated with a scorecard, tracking success in using their expertise to help the line organization improve its performance. For example, the group responsible for driving best practices in reduction of waste tracked operating cost reductions due to reduced scrap, improved yields, and lowered inventories, etc., as key elements of its scorecard. This was in alignment with priorities in the line organization, where each plant was evaluated on overall performance metrics that could be improved by deploying the proven solutions available from the waste reduction group and other staff support groups. This arrangement is reflected in Figure 1.

FIGURE 1. A "MARKETPLACE" OF PERFORMANCE IMPROVEMENT OPTIONS



In this simplified and hypothetical depiction, plants are each responsible for delivering gains in specific improvement targets captured in a scorecard—say 4% reduction in cost per unit, 6% reduction in inventory, 5% increase in production volumes, etc. Meanwhile, the Centers of Excellence are held accountable for their own, initiative-specific targets that could be reached only if their expertise is successfully employed by the various plants—say $10 million of cost reduction through reduced scrap, 5% improvement in company-wide plant uptime, or 3% reduction in corporate-wide days lost to accidents. To hit their annual performance targets, the plants depend on the expertise resident in the support groups. Conversely, to hit their performance targets, the support staff requires application of best practices in the plants in order to generate real dollar impacts.

Corporate leadership did not seek to control or specify which plants employed which initiatives. Rather, they created a system that encouraged local leaders to sort out where their greatest gains could be found. Plant managers had targets to hit, and they had help to draw upon in hitting these targets, but which help they chose to employ was left largely to them. Meanwhile, Centers of Excellence were accountable for having a given cumulative impact on plant operations, but there was no blanket expectation that every plant would employ the same blend of initiatives in hitting its targets. So in the hypothetical example we have here, Plant B is relying heavily upon Initiatives 1 and 2 to deliver its performance gains, and Center of Excellence 3 was seeing its greatest impact in Plants C and D.

In our research, we came to describe this arrangement as a free-market approach to fostering standardization of best practices. Rather than centrally dictating solutions, the organization identified several potential areas of improvement and invested resources in developing centralized expertise in these areas. The decision on how they could best engage with one another to hit their complementary performance targets was then left up to local leaders in the plants and the Centers of Excellence.

We saw very similar line-staff alignment in Defense Contractor, Diversified Corporation, and Heavy Equipment, and in every case, managers were quick to point to this line-staff alignment as an important driver. In our work in defense acquisition, we did not encounter such alignment. Instead, we observed much greater emphasis placed on program management (the line organization in this case) than on functionals (the staff organization). Certainly, holding program managers accountable for cost, schedule, and performance is appropriate. But, this is only the starting point if the goal is to see best practices grow into standard practices. In most cases, the functionals, such as contracting, financial management, engineering, etc., "own" the processes. The program managers simply employ that process in execution of a single program, but the functionals see their processes used over and over.

Given these realities, many of the greatest opportunities to motivate process standardization rest with the functionals. It does make sense to evaluate a single program on its cost, schedule, and performance. But, doesn't it also make sense to evaluate a functional on the aggregated performance of all programs using its processes? For example, if a single medium-size, sole-source acquisition program takes 2 years to place under contract, that is an indictment of program management for that specific program. But, if the average time required for the last 50 medium-size, sole-source contracts to be executed is 2 years, this implies there is a systemic process issue that should be addressed by the functional process owners involved. For the most part, functionals are not under nearly as much pressure as program managers when it comes to improved cost, schedule, and performance, and this misalignment appears to be an important cause of limited success in seeing processes standardized on best practices.

Managerial Forces Creating Push—Driving Compliance

Of the organizations we studied, those successful in standardizing best practices all had leaders who relentlessly pushed compliance to make it happen (Edison & Murphy, 2012; Garvin et al., 2008; Roper, 2011). We observed two strategies for driving compliance—one bureaucratic, and the other behavioral.

In most organizations we studied, bureaucratic controls were clearly used to ensure compliance to standardized best practices (Cash et al., 2008; Chatterjee, 2013; Edison & Murphy, 2012). Sometimes, these controls might be used for specific functions and/or organizational levels. For example, at Defense Contractor, each engineer was approved only for actions specified in four different levels ranging from Level 1 (execute standard work under a supervisor) to Level 4 (authority to set new engineering standards and approve deviation from them). Other times, the bureaucratic controls were applied in a way that cut across functions and levels. For example, the product development process at Heavy Equipment entails a tightly controlled set of hurdles with standard work informing the appropriate next steps at every turn. Changes in this process must receive approval at levels as high as the senior vice president in order to ensure thought has been given to potential cross-organization ripple effects.

> ***In most cases, the functionals, such as contracting, financial management, engineering, etc., "own" the processes. The program managers simply employ that process in execution of a single program, but the functionals see their processes used over and over.***

In the best organizations we studied, these examples of bureaucratic control often complemented the use of what we have termed behavioral controls. While bureaucratic controls rely on explicitly codified organizational rules developed and enforced by management, behavioral controls entail unwritten norms enforced by a broader range of organizational members. For example, managers at General Hospital found it very difficult to dictate standard processes to the doctors using its operating rooms. The operating room is considered the sanctum sanctorum of healthcare—the place where only doctors decide how medicine will be practiced and managers are held outside. However, many operating procedures are replicated hundreds of times each day, and it is entirely reasonable for hospital management to clearly identify any procedures that consistently work better than alternative procedures surgeons may persist in using as a matter of personal preference.

In a situation like this, General Hospital found it very useful to employ behavioral controls to drive compliance through peer pressure. They simply posted data comparing different orthopedic surgery groups on the same operation in the doctors' scrub room, without revealing the identities of the different surgery groups. For example, they posted the average costs and typical percentages of cases with complications for the seven surgery groups putting in artificial knees, simply listing the surgery groups as Group A through Group G. The data revealed that the best group was 40 percent less expensive than the worst group and had 30 percent fewer postoperative complications. Naturally, each surgery group wanted to know which line of data on the table referred to their particular practices. And naturally, surgeons tried to figure out who was doing the best and worst. When the worst performing group saw their data, and recognized that all the other surgeons were also seeing the same data, they quickly adjusted their procedures to bring them more in line with best practices.

Logically, the strongest levels of compliance rely on both bureaucratic and behavioral controls. Consider this quote about military flight operations (anonymous personal communication, June 2008):

> It is drilled in throughout your career that flight operations must take place by the book. There are endless check offs where someone must sign before a particular action is allowed to take place. But, just as important, there is a culture here that is constantly reinforced by leadership. As a result, even if General Buck Rogers tries to climb into a cockpit without the right documentation showing he is checked out for that aircraft, Airman Able will step up to stop him. And rightfully so—we all count on one another to police this.

Such examples make it clear that military organizations know how to combine bureaucratic and behavioral controls to drive adherence to standardized processes. Unfortunately, similar examples in defense acquisition are hard to find.

Conclusions

We have identified six forces that work collectively to influence the extent to which organizations are able to turn their isolated best practices into widespread standard practices. We have also shown how typical defense acquisition organizations are often deficient in each of these. Opportunities exist throughout the defense acquisition community for dramatically increasing the payoff to process improvement efforts in defense acquisition by isolated innovations becoming common practices. But, this will require a broad perspective on the program, and a willingness to engage in systemic change on a number of fronts. Our hope is that this article provides insights into the challenges faced.

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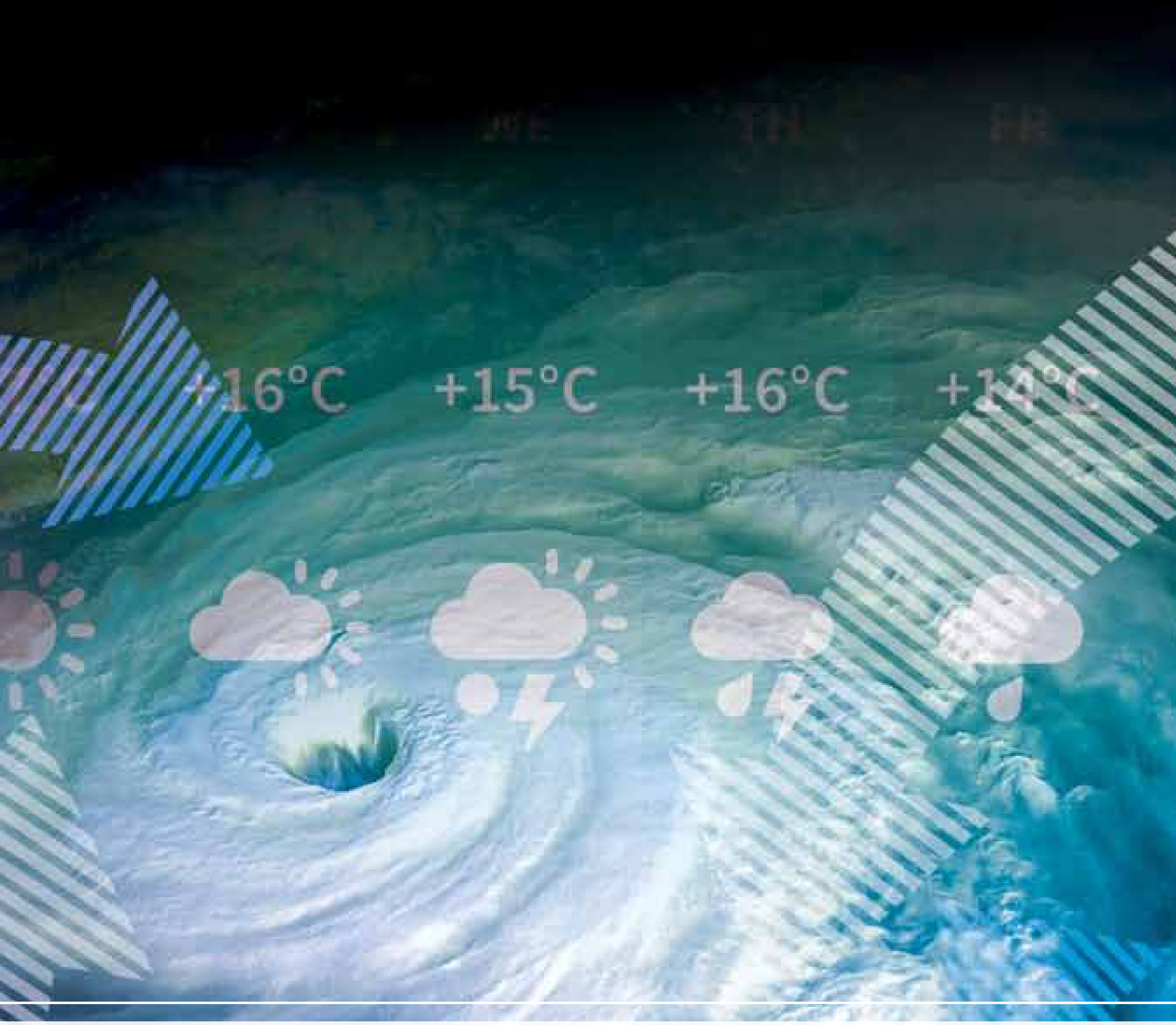
Taming the HURRICANE of ACQUISITION COST GROWTH —*Or At Least Predicting It*

*Capt Allen J. DeNeve, USAF, Lt Col Erin T. Ryan, USAF,
Lt Col Jonathan D. Ritschel, USAF, and
Christine Schubert Kabban*

Cost growth is a persistent adversary to efficient budgeting in the Department of Defense. Despite myriad studies to uncover causes of this cost growth, few of the proposed remedies have made a meaningful impact. A key reason may be that DoD cost estimates are formulated using the highly unrealistic assumption that a program's current baseline characteristics will not change in the future. Using a weather forecasting analogy, the authors demonstrate how a statistical approach may be used to account for these inevitable baseline

Image designed by Diane Fleischer



changes and identify related cost growth trends. These trends are then used to reduce the error in initial acquisition cost estimates by over one third for major defense acquisition programs, representing a more efficient allocation of $6 billion annually.

Keywords: *Capabilities Development for Rapid Transition, Joint Urgent Operational Need (JUON), Lethal Miniature Aerial Munition System, Operation Enduring Freedom, Operation Iraqi Freedom (OIF), Program of Record, Rapid Equipping Force*

The Not-So-Perfect Storm

Inaccurate cost estimates have long plagued Department of Defense (DoD) acquisition efforts. Despite the myriad acquisition reforms, and abundant detailed guidance on cost estimating best practices, accurately predicting the eventual cost of a weapon system remains difficult. A Government Accountability Office (GAO) study of all 96 active major defense acquisition programs (MDAP) in 2011 showed a total cost increase of over $74 billion in that year alone (GAO, 2012a)—an amount that would have paid for the 2013 defense sequestration cuts nearly twice over. The total MDAP portfolio cost continued to grow into 2013, despite a trend of reduction in the number of programs (GAO, 2014). A RAND study of completed major acquisition programs showed that the average cost estimate error measured from Milestone B is about 65 percent (Arena, Leonard, Murray, & Younossi, 2006a). This figure is an average of overestimates and underestimates; the absolute error is even higher. While researchers and practitioners may disagree on the efficacy of recent acquisition reforms upon improving cost estimates, clearly, there is ample room for improvement.

Perhaps the problem does not lie with the accuracy of the cost estimates, but with the fact that these estimates are accurately estimating the wrong thing. For example, when the RAND study corrected the cost data for changes in procurement quantity, the average cost errors dropped by over 20 percent (Arena et al., 2006a), and the GAO (2012a) study attributed nearly 40 percent of the $74 billion increase to quantity changes. If we expect accurate estimates of the final cost of acquisition programs, then we must take into account the uncertainty associated with program baselines upon which these estimates are based. We propose a method for correcting initial acquisition cost estimates using observed baseline deviations from similar past programs, thus reducing the average cost growth over these early estimates.

The Defense Acquisition University (DAU) defines cost growth as "the net change of an estimated or actual amount over a base figure previously established."[1] Many studies cite changes to the Acquisition Program Baseline (APB) as among the most significant sources of cost growth (Arena et al., 2006a; Drezner, Jarvaise, & Hess, 1993; GAO, 2012a). These studies often correct the cost estimates for these changes in an attempt to determine the programmatic causes for the cost overruns. In this way, researchers "maintain the integrity of the baseline" (Drezner et al., 1993, p. 11). These baseline-corrected analyses

> ***A more accurate prediction of the eventual cost of an acquisition program provides a better assessment of that program's affordability, thus better informing affordability decisions.***

are useful for driving acquisition reform, but they are less useful for informing resource allocation and affordability assessments, which are inherently more concerned with accurate prediction of actual program expenditures.

Will Cost, Should Cost, and Real Life

In a 2011 memorandum from the Assistant Secretary of the Air Force, Financial Management and Comptroller, and the Air Force Acquisition Executive (Department of the Air Force, 2011), the Air Force established the practice of generating two different cost estimates dubbed Will Cost and Should Cost. The Should Cost estimate is "based on realistic technical and schedule baselines and assumes success-oriented outcomes." In contrast, the Will Cost estimate is based on an independent estimate that "aims to provide sufficient resources to execute the program under normal conditions" (Department of the Air Force, 2011, p. 4). This notion that a program may cost something more than it should cost implicitly acknowledges that things don't always go as desired. Also, this concept sets the precedent that allowances may be made for difficulties through cost-estimating relationships that reference past development and production efforts as a benchmark.

In actuality, the Should Cost estimate does not incorporate enough realism. For example, common sources of cost growth, such as procurement quantity changes, are not included in the Should Cost estimate since this estimate is still based on the APB. This baseline specifies parameters such as procurement quantity, performance characteristics, program duration, and so on. However, these baselines almost never remain constant (Drezner & Krop, 1997), leading inevitably to changes in program cost and crippling early estimating efforts.

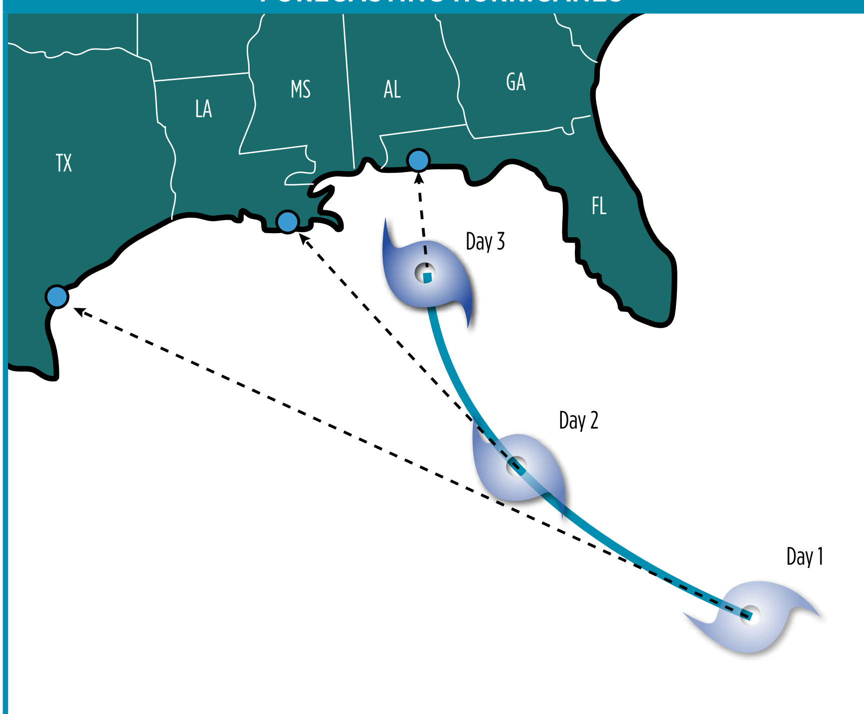
A more accurate prediction of the eventual cost of an acquisition program provides a better assessment of that program's affordability, thus better informing affordability decisions. Therefore, the DoD needs a method for accurately estimating the final cost of an acquisition effort without relying on a fixed baseline. In this research, we have developed a novel method to correct early program cost estimates using high-level descriptive programmatic parameters. Advanced regression techniques establish a relationship between these parameters and the cost estimate error of past programs, and then use this relationship to predict estimate error in similar future programs. This method is dubbed "macro-stochastic" estimation (Ryan, Schubert Kabban, Jacques, & Ritschel, 2013, p. 3).

The National Oceanic and Atmospheric Administration (NOAA) uses a similar technique in the forecasting of hurricanes, a domain that has seen prediction accuracy triple in the last two decades (Silver, 2012). This fact is intriguing, because the challenges associated with predicting the path of a hurricane are remarkably similar to those of trying to predict and budget for the cost trajectory of a DoD program. In both cases, an extraordinary number of discrete, nonlinear elements all interact in exceedingly complex ways, serving to greatly complicate the task of predicting overall system behavior. And while the two phenomena both present similar estimating challenges, the modeling approaches and reporting conventions vary significantly.

We Know What a Bad Prediction Looks Like

For a moment, imagine that meteorologists forecast hurricanes in the same manner that the DoD budgets for acquisition programs. The local news channel reports that a hurricane has formed in the Caribbean. An expert team of meteorologists carefully examines the key characteristics of this newly formed hurricane, including its current location, size, speed, and heading. Based on this information, the meteorologists then officially announce their prediction for the hurricane: it will be a Category 2 hurricane that makes landfall at the intersection of Main Street and Third Avenue in Corpus Christi, Texas. The residents of Corpus Christi are notified of the threat. But, 24 hours later, the meteorologists follow this same process, and provide an equally detailed—but vastly different—prediction. The Day 2 prediction is updated to take into account a new trajectory and larger size; now the storm is predicted to make landfall at the Northeast corner of the Walmart store in Cameron, Louisiana, as a Category 3 hurricane. The next day, this process repeats, predicting an even larger hurricane with a new landfall point in the parking lot of the Spinnaker Beach Club in Panama City, Florida. These volatile predictions are depicted in Figure 1.

FIGURE 1. AN ACCURATE (BUT LESS USEFUL) METHOD FOR FORECASTING HURRICANES



You might reasonably have many concerns about these estimates. For example, how likely is it that the hurricane will actually make landfall at these precise locations? You might wonder why each estimate only considers the current state of the hurricane as opposed to how it might change over time. And, of course, you might be highly skeptical of any set of estimates that varies so widely. But, this scenario does have some unfortunate similarities with the DoD cost-estimating and budgeting processes. Although cost estimators carefully account for uncertainty in their cost estimates (based on a fixed APB), the official prediction is recorded into the budget as a point estimate. Their cost estimates typically include no consideration for a change in trajectory, and no indication of uncertainty in the eventual budget request. Just like in our fictitious forecasting scenario, we have an early prediction, but it is not a very good one since it is almost guaranteed to change. Updating the absurdly specific budget request at each milestone is not an adequate solution for addressing this change since substantial resources will have already been committed according to the original baseline. In fact, a common engineering adage presumes that 75 percent of the design cost is committed in the first 25 percent of the life cycle (Blanchard & Fabrycky, 2011).

Of course, this is not the way meteorologists forecast hurricanes. NOAA uses supercomputers running millions of advanced physics simulations to calculate the outcomes of minor changes in the weather's initial conditions, and these outcomes are combined to form a probabilistic prediction (e.g., "There is a 10 percent chance of rain today"). These simulations are supervised by experienced meteorologists, using their knowledge of past weather patterns to improve forecast accuracy by up to 25 percent over computer simulation alone (Silver, 2012). This marriage of cold calculations and "squishy" probabilistic judgments carries over to hurricane prediction; to predict the storm's path, NOAA uses this method of human-mediated simulation (Ferro, 2013).

But for the prediction of hurricane strength, forecasters turn to what is essentially macro-stochastic estimation. They "compare basic information from the current storm, like location and time of year, to historic storm behavior," and use this information to predict the storm's strength (Ferro, 2013). In other words, top-level descriptive parameters are used to associate this storm with previous storms. The implicit assumption is that the current hurricane will perform similar to past hurricanes, as long as the right descriptive parameters are chosen. This combination of detailed simulation, coupled with statistical techniques (not to mention a healthy respect for uncertainty) produces the most useful estimate for informing evacuation decisions. That is, it results in a reasonably accurate prediction as early as possible.

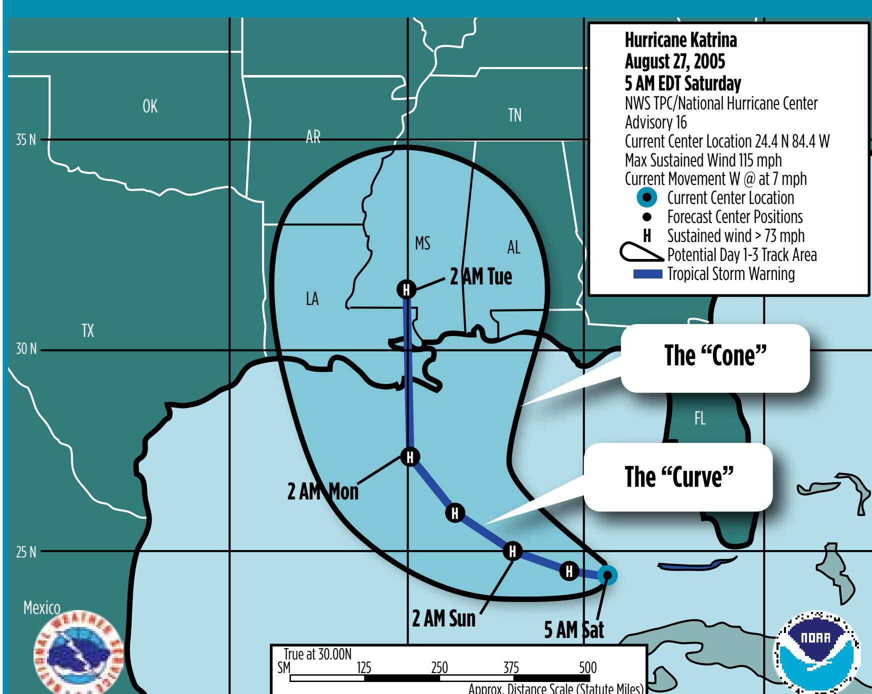
However, embracing uncertainty is not synonymous with imprecision; for a prediction to be useful, it must not be overly vague. Most people are acquainted with the graphic that weather forecasters use to illustrate the expected path of hurricanes; an example is shown in Figure 2. This familiar visual form of prediction has two important elements:

1. The Cone: the region of uncertainty that shrinks as the storm approaches land and provides an idea of the confidence in the estimate.

2. The Curve: the change in trajectory that indicates the predicted path the storm will take.

FIGURE 2. NOAA HURRICANE TRACKER, SHOWING LANDFALL PREDICTION FOR HURRICANE KATRINA

Image Adapted from NOAA National Hurricane Center

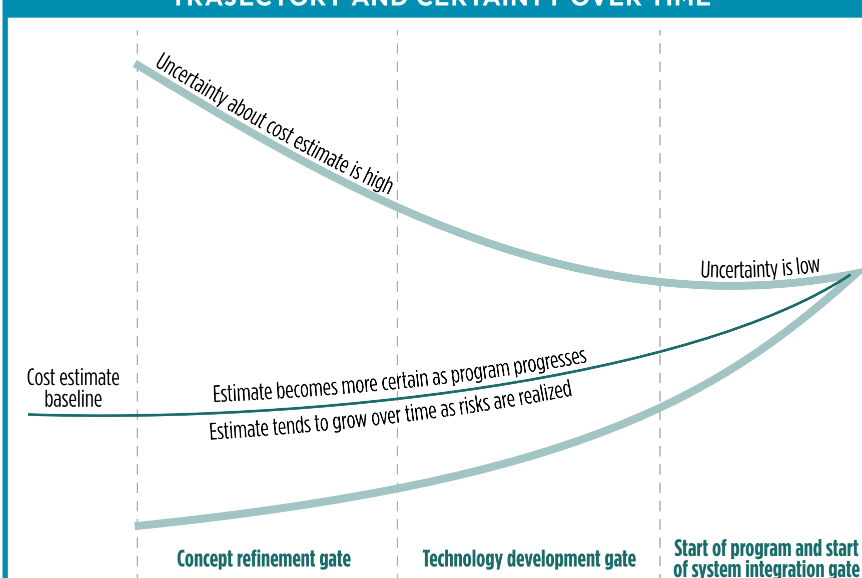


Note. Adapted from *Cost Estimating and Assessment Guide* (GAO-09-3SP), by Government Accountability Office, 2009, Washington, DC.

The Cone

The entire body of recent DoD cost-estimating guidance emphasizes the importance of risk analysis, sensitivity analysis, and the reporting of confidence in the program cost estimates (GAO, 2009; U.S. Air Force, 2007).[1] In fact, one might admire the similarity between NOAA's hurricane-tracking chart and a notional graphic from the *GAO Cost Estimating and Assessment Guide* (Figure 3) that illustrates the trajectory of a cost estimate baseline, with its accompanying cone of uncertainty (GAO, 2009). Unfortunately, the complex DoD process for turning an estimate into a budget does not possess a mechanism for incorporating uncertainty. Despite the best efforts of cost analysts to inform their customers of the confidence and possible risk in their calculations, these warnings are often interpreted as being too vague—a sentiment once expressed by an irate Harry S. Truman, who famously declared: "Give me a one-handed economist! All my economists say, 'on the one hand, on the other' " (Krugman, 2003). Incorporating uncertainty in budgeting activities requires a transformation in the way we think about resource planning. The first step in catalyzing such a revolution is likely to make provisions (or mandates) for reporting cost estimate

FIGURE 3. CONCEPTUALIZATION OF COST ESTIMATE TRAJECTORY AND CERTAINTY OVER TIME



uncertainty and confidence in acquisition status reports.[1] However, acquisition reform is beyond the scope of this study. Instead, we will focus primarily on "The Curve."

The Curve

It is not always reasonable to expect that the DoD can acquire a new weapon system for the Milestone B "sticker price." As one author recently noted, "Cost Discovery might be a better term for the process of updating estimates, because in retrospect it was clearly impossible to produce the stated capabilities for the original price" (Cancian, 2010, p. 396). It is rational to expect the rigors of research, development, and testing after Milestone B to uncover additional requirements that necessitate additional funding. But, if we are unable to completely avoid this "cost discovery," perhaps we should focus our efforts on predicting it. For example, consider the following questions:

- Is it true that an Air Force fighter aircraft program is likely to procure fewer aircraft than originally planned?
- Do Joint programs have significantly higher acquisition cost growth than non-Joint ones?
- Is the occurrence of a Nunn-McCurdy breach in a program a good indicator of future threshold breaches?

If we are able to hypothesize a relationship between these top-level program characteristics, then it is possible to examine past data to test if this relationship exists. Furthermore, if the relationship between these elements is, in fact, deemed statistically and practically significant, then we may apply this relationship to correct estimates in new programs. Macro-stochastic estimation is used to accomplish these goals.

Macro-Stochastic Estimation

To implement the macro-stochastic estimating technique described earlier, we first have to decide what high-level (macro) parameters are the most strongly associated with cost estimate errors. Next, we have to decide what constitutes a "similar program" so that we may apply the technique correctly on future data. In support of these pursuits, we have created a database that tracks 75 distinct characteristics of MDAPs.[2] The Selected Acquisition Reports (SAR) for these programs are the source for our database.

Programs that have expended at least half of their planned funding are considered for entry in the database since these programs have sufficient data to measure trends in early program life. Also, only programs with a Milestone B date of 1987 or later are included. This cutoff date allows for a sufficient number of programs to estimate key characteristics and also maintains some continuity and relevance with current programs (Smirnoff & Hicks, 2007). This filtering process results in a sample of 937 SARs describing 70 programs from the Army, Navy, and Air Force. For each SAR, we compare the program's estimate of total acquisition cost against the actual cost specified in the program's final SAR. This ratio of estimated cost from a particular SAR to the final cost is defined as the Cost Growth Factor (CGF). For example, a program with a CGF of 1.3 indicates that the actual cost of the program was 30 percent higher than the original estimate. A program that perfectly estimated its final cost would have a CGF of 1.0.

A statistical technique known as mixed-model regression is applied to identify the parameters most strongly associated with changes in the final cost of a given program. This advanced statistical methodology is required due to the longitudinal nature of SAR analysis; that is, repeated measurements of the same program are expected to be correlated, violating a fundamental assumption of basic linear regression. Iteratively testing parameters in the dataset results in an efficient model of CGF containing the six parameters shown in Table 1.

It may seem like an oversight to omit an explanation of how each of these parameters affects CGF (that is, positively or negatively). In this case, the reason for this omission is related to the mixed-model methodology, and would surely have frustrated former president Truman, as the relationship varies depending on the program. Importantly, these six parameters are combined in different ways to create models tailored to specific groupings of programs, as described in the discussion that follows.

TABLE 1. SIGNIFICANT MODEL PARAMENTERS		
Parameter	**Description**	**Fixed/Variable**
Service Component	Identifies the executive military service (Army, Navy, or Air Force) that leads the acquisition program. Marine Corps programs are identified as belonging to the Navy.	Fixed
Development to Production Ratio	The ratio of the number of years a program spends in development to the number of years the program spends in production.	Variable
Count of Development APBs	This parameter tracks the number of times a new baseline is generated during the development phase.	Variable
Acquisition Cost	The total estimated program acquisition cost, as reported annually in the SAR.	Variable
Quantity Change	This parameter is tracked as a ratio of the procurement quantity planned in a given year to the original Milestone B procurement quantity.	Variable
Year Count	The sequential numbering of the program year, starting with Milestone B as year one. The presence of this parameter ensures the model is capable of predicting the estimate trends across time.	Fixed

Method

The mixed-model regression technique introduces flexibility that allows the analyst to generate different models for different groupings of programs. To return to our hurricane example, storms in the Caribbean might behave differently than those in the Atlantic. This difference may be taken into account by grouping the hurricane data into two bins, perhaps called Caribbean and Atlantic, and allowing the regression to generate separate estimates according to this partition. This feature is very powerful, since it can resolve patterns that might otherwise be averaged out when the dataset is analyzed as a whole. More importantly, this feature allows us to bin acquisition programs into groups according to similarities in the behavior of their cost estimate error. When we wish to predict the CGF in a new program, we can apply the most appropriate model of estimate errors by determining the most suitable group for the new program.

The way programs are grouped is critical to the predictive power of the macro-stochastic technique. In theory, we could put all programs into the same group; but what we gain in broad model applicability, we sacrifice in accuracy. If the cost growth behavior for each of these programs was essentially the same, we wouldn't be so regularly thwarted when trying to produce a useful budget. Conversely, we could go with the opposite extreme and create a regression that examines each program individually by only assigning one program to each group. This grouping method results in a different model for each program and reduces nearly 99% of the error in program cost estimates! However, this accuracy is gained at the expense of utility. Future programs cannot be assigned to an existing group that is uniquely defined. The critical task, then, is to determine the most beneficial way to group the programs in order to balance accuracy with predictive capability.

Program Grouping

In this study, programs are grouped according to the categorical variables that are most strongly correlated with the CGF. These variables are simply characteristics of the program that are known in the first year, and reported in the first SAR. For example, final cost growth tends to be higher for new-start programs than programs that are essentially modifications or variants of existing weapon systems. Therefore, identification of program iteration is used to distinguish program groupings. The implicit assumption with this approach is that programs with similar overall cost growth will also exhibit similar cost growth patterns. The variables selected to bin programs are defined below.

1. Program Type. Based on the program description in the SAR, each program is placed into one of seven categories: Aviation, Electronic, Ground Vehicle, Maritime, Munition, Space, and Space Launch. These categories are consistent with previous program type categorizations (Arena et al., 2006a; Drezner et al., 1993).

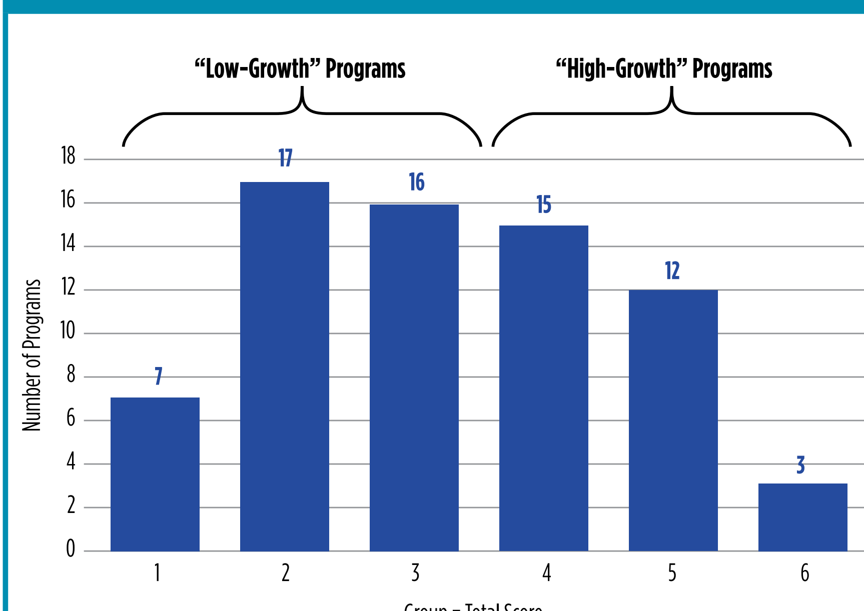
2. Iteration. This variable states whether a program is new, a lettered-variant on an existing program (e.g., the F-16 C/D), or a modification to an existing program (e.g., the C-5 Avionics Modernization Program).

3. Number of Years Funded. This variable describes the number of years the program is expected to be funded. This variable may change due to funding volatility.

4. Joint. This binary variable indicates whether a program is Joint between two or more Services.

Program groups are created by dividing each of the variables into levels, ensuring sufficient sample size within each level. A program is assessed a CGF "score" based on the applicable level for each of the four variables. The program group is the sum of the CGF scores across the four variables. Each program is scored in this manner, and the total scores from each program form the six program groups shown in Figure 4.[3]

FIGURE 4. PROGRAM GROUPS RESULTING FROM CGF SCORES



Validation and Results

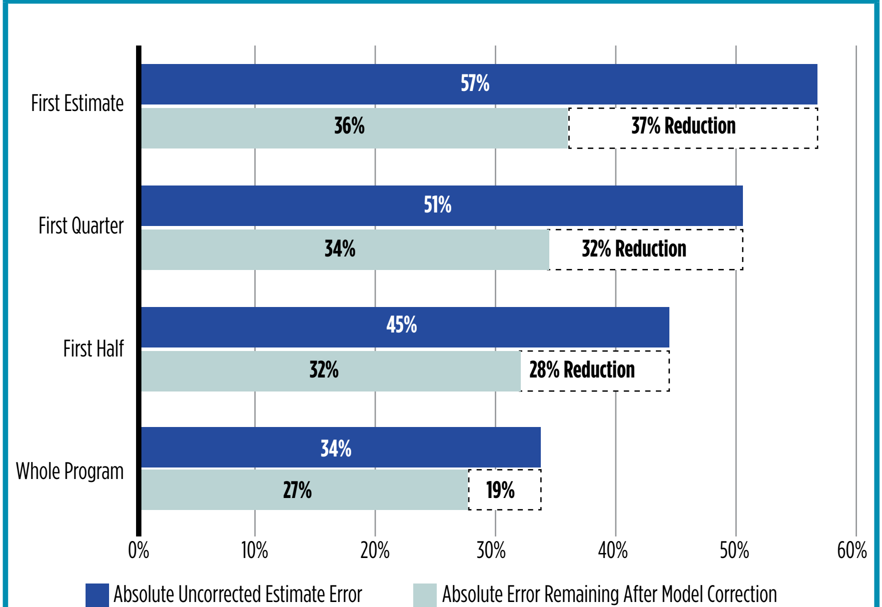
The mixed-model regression uses the program groups in Figure 4 to fit different models using the significant CGF predictors shown previously in Table 1. However, due to relatively few programs in certain groups, validating the model is necessary without omitting too many of our samples for this purpose. Consequently, we validate the model using a technique that omits program data in a round-robin fashion, predicting the CGF of the omitted program and then replacing the data to make the prediction for the next omitted program. This validation is a type of Leave One Out Cross-Validation tailored to multilevel or mixed models (Ryan et al., 2013). It results in the aggregation of 70 separate analyses (one for each program) into a single set of results that reflects the expected predictive power of the macro-stochastic model. The validated model produces a set of predicted CGFs for every program estimate throughout the life of every program in our sample. If this version of the model is deemed reasonably powerful, then the original fitted model is considered validated and is the final model reported for inference.

Using the validated results, the predicted CGF for any SAR that meets the established completion criteria may be used to correct the cost estimate in that SAR, but some of these corrections will be more useful than others. Since the SAR estimates get progressively better over time, there is equivalently less CGF error for the model to correct, thus reducing the average predictive performance of the model as a program matures. Consequently, the macro-stochastic technique is most useful when applied to correct the earliest cost estimates in a program. In fact, for each additional percentage of program expenditure, the model loses approximately three-quarters of a percent of its predictive power.

The 70 programs in our dataset displayed a mean CGF of 1.44, measured from the initial SAR estimate. This means that the programs underestimated their eventual cost by 44%, on average. However, this is an average of underestimates and overestimates. For the purposes of resource allocation, under and overestimation of budgetary requirements may both be considered detrimental because dollars allocated to one program cannot be easily transferred to another. Since the model seeks to minimize cost estimate errors regardless of direction, the absolute estimate error is a more appropriate measure. Our sample showed a mean absolute error of 57%.

In contrast, after applying the macro-stochastic technique, the model-corrected CGF for these initial estimates averaged 0.93—slightly overestimating, but closer to the ideal 1.0 CGF. As shown in Figure 5, the average absolute error for model-corrected estimates was 27%, representing a 19% reduction in the average absolute cost estimate error, across all programs. However, model performance is best in early program life; the average error reduction in the first estimate is 37%. Also, since the six program groups are assigned by assessing the severity of their cost growth, we expect that the most significant improvement will be seen when the model is applied to the "high-growth" programs. When the algorithm is applied to the first estimate of programs in CGF categories four through six, 90% of these estimates are improved, with an average error reduction of 45%.

FIGURE 5. SUMMARY OF VALIDATED MODEL PERFORMANCE ACROSS ALL 70 PROGRAMS



Reporting model performance as a percent improvement is useful because it normalizes programs of disparate cost. However, since our research focuses on real dollars, it is important to convert the percent error reduction into a dollar amount to demonstrate model efficacy. The absolute percent error for each program is multiplied by its final cost and converted to base year 2013 dollars in order to establish the total dollar amount reallocated by the validated model. The aforementioned 19% reduction in error equates to $119.5 billion, in base year 2013 dollars. If the total cost of these programs is scaled to equal that of the current DoD MDAP portfolio (DoD, 2013), then this macro-stochastic model could potentially allocate $6.24 billion more efficiently every year, if consistently applied to the first estimate of new MDAPs.

What This Technique Is Not

These results clearly illustrate the utility of the macro-stochastic cost-estimating approach. But, as is often the case with statistical tools, it is perhaps equally important to manage expectations by explaining a few of the applications for which this technique is ill-suited.

1. Adjusting cost estimates at the program office level. The efficacy of the model deteriorates rapidly and, even when applied to the first estimate of every program, only about 72% of program estimates are improved. This notion that estimates are only improved on average can be a significant source of doubt when it suggests that a program's rigorously developed estimate might be 44% too low. However, the average cost of programs is sufficient for informing better affordability decisions when considering a portfolio of assets.

2. Placing blame and driving acquisition reform. Macro-stochastic estimation eschews the typical cause-and-effect relationship that so many other acquisition studies seek to uncover. Rather, the model draws its power from the correlation between seemingly unrelated things. For example, it would be incorrect to say that the Service Component causes cost growth; it is simply an observed correlation. This lack of causality makes this model ill-suited for suggesting changes to the acquisition process.

3. Placing bounds on a traditional cost estimate. The full text of this study (DeNeve, 2014) explains the prediction intervals that surround the estimates of CGF. However, these alone do not constitute the "cone of uncertainty" discussed earlier in this article. With changes to the APB, the distribution around the predicted CGF and the cost estimate will change. Both of these distributions must be taken into account when placing bounds on the model-corrected final cost estimate. This is a subject for future work.

Conclusions

The existing paradigm for reporting acquisition cost based on a fixed APB results in unrealistic budgets and chronically inefficient resource allocation. In the current environment of fiscal restraint, embracing uncertainty can help provide a more realistic view of a program's true affordability. Acknowledging the likelihood of changes to a program's baseline grants the freedom to leverage past data and predict trends in cost-estimate performance. While not suitable as a low-level cost estimating tool, this study demonstrates such a method to reduce cost-estimate error in the earliest estimates of major defense programs, helping to stabilize long-term, portfolio-level budgets. As demonstrated by Figure 5, our model achieves the most significant error reduction early in program life, when accurate estimates are crucial for resource allocation and affordability decisions. In fact, nearly half of the estimate error is reduced when the model is applied early to the most growth-prone acquisition programs. As with hurricane forecasting, the optimal approach for acquisition cost estimation is likely a combination of techniques that focuses on providing the most useful estimate, even if this means embracing the uncertain nature of defense acquisition.

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Endnotes

[1]The *Defense Acquisition Guidebook* dictates that MDAPs "must state the confidence level used in establishing a cost estimate…in the next Selected Acquisition Report prepared in accordance with 10 U.S.C. § 2423" (DAU, n.d., Chap 3, §3.4.1). The referenced section of U.S. Code contains no such requirement, and few SARs currently report confidence in their estimates.

[2]MDAPs are the largest programs in the DoD, defined by having more than $509 million for Research, Development, Test & Evaluation, or more than $3 billion for procurement in Base Year 2010 dollars (Weapon Systems Acquisition Reform Act, 2009). In fiscal year 2014, MDAPs constituted 40 percent of the acquisition funding for the DoD (DoD, 2013) and since 1969, they have been required to submit a standardized annual report of their status, called the Selected Acquisition Report (GAO, 2012b).

[3]This scoring methodology is explained in far greater detail in the full text of the study (DeNeve, 2014).

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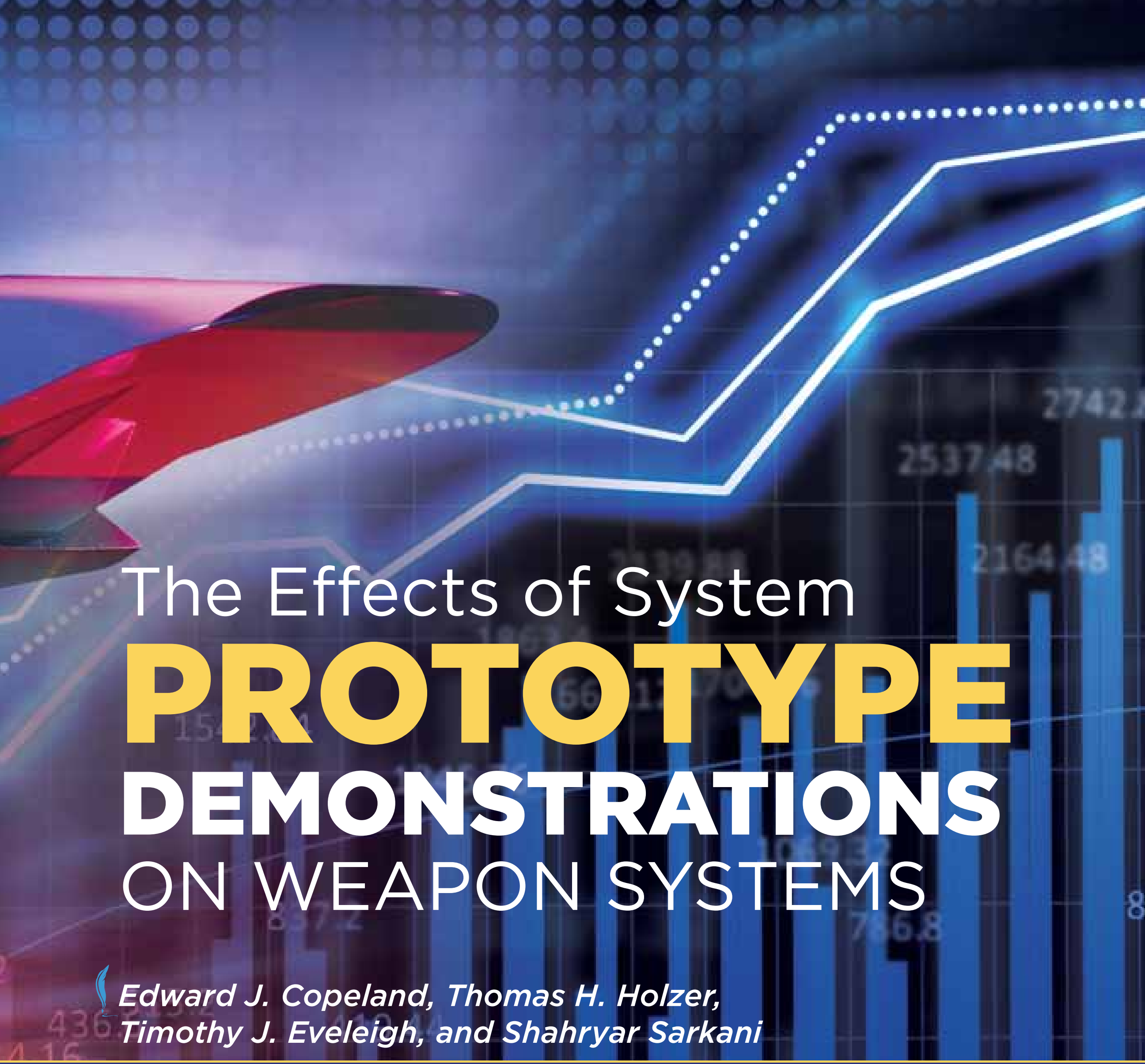
The inability of Department of Defense (DoD) programs to sufficiently reduce technology risk prior to entering formal systems development has between 2007 and 2012 contributed to a 13 percent cost growth in weapon systems acquisition and a 17 percent increase in cycle time to deliver initial operational capability. With the advent of key legislation and resulting DoD acquisition reform initiatives, weapon systems programs are now required to enforce a technology development strategy that can foster true risk reduction prior to entering systems development. A key enabler to reducing technology risk and

Image designed by Diane Fleischer



The Effects of System PROTOTYPE DEMONSTRATIONS ON WEAPON SYSTEMS

Edward J. Copeland, Thomas H. Holzer, Timothy J. Eveleigh, and Shahryar Sarkani

thereby accelerating design maturity is the use of system prototype demonstrations. The objective of this article is to present research findings on the "effects of system prototype demonstrations on weapons systems development" for major defense acquisition programs. The results of this research will better inform systems engineers and contribute to improved technology development strategy.

Keywords: *system prototype, technology demonstration, technology maturity, design maturity, program performance*

The Department of Defense (DoD) has historically struggled to implement effective risk-mitigation strategies in the development of highly complex weapon systems, as evidenced by increasing cost and schedule growth over the past several decades (General Accounting Office, 1999; Government Accountability Office [GAO], 2006b). The inability of DoD programs to sufficiently reduce technology risk prior to allowing a program to enter formal systems development has, as measured from 2007 to 2012, contributed to a 13% cost growth in weapon systems acquisition, and a 17% increase in cycle time to Initial Operational Capability, or IOC (GAO, 2013). Acquisition cycle time is defined as that span of time from program start to deployment of IOC to the warfighter. When compared to First Full Estimates, the DoD major defense acquisition program (MDAP) portfolio total acquisition cost had grown an average 38%; correspondingly, product cycle time increased an average 37% (GAO, 2013).

First Full Estimates, as defined by the GAO, are the original total acquisition cost estimates established at program development start (GAO, 2012, p. 36). The GAO estimates for MDAPs and their total acquisition costs are collected from DoD Selected Acquisition Reports (SAR) and consist of research and development, operations and maintenance, and military construction costs (GAO, 2012, p. 171). Clearly, this performance trend has been unacceptable, and further attention is required to manage technology risk effectively.

Today's economic climate continues to threaten available DoD funds and underscores the need for streamlined but effective systems engineering. Smart application of cost-effective tools and techniques, such as the use of system prototype demonstrations, should be leveraged to ensure maximum payback per dollar towards risk reduction. The cost of using prototypes, balanced with value-added risk-reduction returns, will contribute to program "Should Cost" savings. The phrase Should Cost, institutionalized by DoD as part of Better Buying Power 2.0, is an initiative for MDAPs to eliminate inefficiencies and capitalize on cost-saving opportunities (Carter & Mueller, 2011). In a recent, concise, and highly convincing article published in *Proceedings*, the U.S. Naval Institute's flagship magazine, VADM David Dunaway, Commander of the Naval Air Systems Command, wrote about today's economic climate: "In the face of decreasing budgets, rapidly evolving threats, and a shift in defense strategy, ... it's imperative that every dollar spent increases warfighting capability" (Dunaway, 2013, p. 326).

> ***Today's economic climate continues to threaten available DoD funds and underscores the need for streamlined, but effective systems engineering.***

Through the use of descriptive statistics and empirical analysis, this article summarizes the comparative performance for MDAPs that did and did not invest in system prototype demonstrations for early risk reduction prior to entering system development, otherwise referred to as Engineering and Manufacturing Development (EMD). Additionally, for those MDAPs that did use prototype demonstrations over this past decade, program performance was examined for any impacts coincident with the adoption of related key systems engineering policy and legislation.

With the Defense Acquisition Management System (DAMS) model as a conceptual framework, key hypotheses were evaluated using empirical analysis of historical evidence and trends to help validate observed system behavior. The effects of pre-EMD system prototype demonstrations on program performance were examined using observed impacts to technology readiness and weapon system design maturity. The data analysis does not highlight any individual program specifics, but applies a macro-level analysis of aggregated data to characterize observed program performance as a function of key predictor variables.

The authors anticipate that the findings of this research would help to (a) better inform program managers and systems engineers on the effects of system prototype demonstrations on weapon systems development; (b) better provide insightful knowledge to develop more effective technology development strategy; and (c) better implement "true" risk reduction measures, per DoD guidance (Kendall, 2012) before entering the EMD phase. The context of "true" in reference to risk reduction is meant to imply pre-EMD system development mitigation activities that can indeed reduce the risk of cost and schedule growth, and minimize product cycle time to the warfighter. System prototype demonstrations not only validate the state of technology maturity for enabling technologies, but also provide for early mitigation of system/subsystem integration risk. Consonant with DoD's goals for improving Better Buying Power, this research also provides additional insight into whether perceived gains from pre-EMD prototype demonstrations are actually being realized.

Prototype Demonstrations —A Historical Perspective

As demonstrated in the early 1900s, whether it's the Wright brothers' experimentation leading up to the first successful flight of the Wright Flyer, or Samuel Langley's attempts to launch an Aerodrome for the first time off a modified houseboat at sea, our nation's industry has leveraged system prototype demonstrations for over a century. Figure 1 portrays two historical moments in time where system prototypes were used to reduce early aviation technology risk.

Prototypes provide the designer a useful tool with which to visualize and transition new ideas into development using an archetype, initial model, or early pattern of the envisioned end product. Industry has leveraged prototypes with great success as a necessary enabler and bridge to introduce new products into the marketplace. Although the value of prototypes may seem obvious, historically the use of prototypes and the perceived return on investment has been a subject of debate. The following chronology highlights DoD's changing opinion on the use of prototype demonstrations:

- (Favorable) As early as the 1930s, industry commonly built engine-aircraft combination prototypes as a form of aircraft development risk mitigation (Drezner, 1992).
- (Favorable) Post-World War II, in the mid to late 1940s, competitive prototype flight testing occurred with the transition of propellers to reciprocating engines (Smith, Barbour, McNaugher, Rich, & Stanley, 1981).
- (Not Preferred) In the 1950s, since prototypes were not representative of full-scale development integrated designs, the opinion was that the practice was wasteful and non-value added (Smith et al., 1981).

FIGURE 1. EARLY EXAMPLES OF AVIATION SYSTEM PROTOTYPE DEMONSTRATIONS

Samuel Langley's Aerodrome, December 8, 1903

Wilbur Wright's 1st Successful Flight, December 17, 1903

Note. Photos courtesy Library of Congress (Smithsonian Libraries, n. d. a and b).

- (Not Preferred) With the advent of the digital computer age in the 1960s, a prevailing philosophy existed that theoretical analysis would be sufficient to predict systems design performance without the need for costly prototypes (Smith et al., 1981).

- (Favorable) Coincident with the first issuance of DoD Directive 5000.1 in 1971, prototyping was re-introduced as a key risk reduction tool as a result of then-Secretary of Defense David Packard's "Fly-Before-Buy" promulgated policy. Competitive prototypes were encouraged with less dependence on concurrent development and paper studies before entering Full-Scale Development (DoD, 1986).

- (Favorable) In 1986, the President's Blue Ribbon Commission on Defense Management, referred to as the Packard Commission, reported the need for rigorous testing of system prototypes prior to Full-Scale Development, again emphasizing a Fly-Before-Buy philosophy (DoD, 1986). Subsequent legislation was introduced in 1987, which mandated that DoD develop and test competitive prototypes for MDAPs before awarding a production contract (Glass, 1988).

- (Favorable) As a result of a General Accounting Office (1999) study rcommendation, in 2001 DoD adopted the use of Technology Readiness Levels (TRL) as a means for MDAPs to manage the maturity of technology entering system development (Technology Readiness, 2010). The National Defense Authorization Act (NDAA) of 2006 established statutory law for the Milestone Decision Authority to certify that all critical technologies (i.e., referred to as critical technology elements) have been demonstrated in a relevant environment (i.e., TRL 6) before granting an MDAP approval to enter EMD (NDAA, 2006). In 2007, then-Under Secretary of Defense for Acquisition, Technology and Logistics John Young released a memorandum, "Prototyping and Competition," directing the Services and Defense Agency proponents for MDAPs to "formulate all pending and future programs with acquisition strategies and funding that provide for two or more competing teams producing prototypes through milestone (MS) B"

(Young, 2007). The Weapon Systems Acquisition Reform Act of 2009 (WSARA) introduced legislation that enforced specific risk-reduction efforts prior to entering system development, including engagement with industry before EMD for technology maturation; competitive prototyping; and the establishment of a system allocated baseline at a system-level Preliminary Design Review (WSARA, 2009).

What Constitutes a Prototype?

The term "prototype" has many definitions depending on the context and need. First, it is important to understand the difference between prototyping and a prototype. In general, prototyping is a process to foster creativity and new ideas, visualize novel application and enabling technologies, reduce uncertainty and increase the advancement of knowledge, and highlight the art of the possible. Prototypes provide the mechanism to "uncover truth" (National Research Council, 2013, p. 3) through observed and controlled experiments that allow for the collection of quantifiable data to explore, develop, validate, and improve performance prediction models or theories.

The primary purpose for using a prototype is to mitigate risk (cost, schedule, or performance) to product development and to the timely delivery of an affordable and compliant end-item to the customer. Prototypes focus on high-risk areas considered essential to achieve system performance and are deemed important to achieve market or user introduction. The cost and relative complexity that a prototype can take on will vary depending on the need and the significance of the function being mitigated. From small-scale, relatively simple models for desktop experiments to larger, more complex full-scale integrated system demonstrators, the primary goal for the use of a prototype is to yield insightful knowledge that can be used to reduce end-item risk.

A prototype fundamentally is used to demonstrate increasing levels of system integrated solutions in stages of representative environments to meet expected operational performance in mission-relevant scenarios. When considering the general nature of prototyping, a RAND Corporation study (Drezner, 1992) concluded that a prototype is best defined as:

> … a product (hardware and/or software) that allows hands-on testing in a realistic environment. In scope and scale, it represents a concept, subsystem, or production article with potential utility. It is built to improve the quality of decisions, not merely to demonstrate satisfaction of contract specifications. (p. 9)

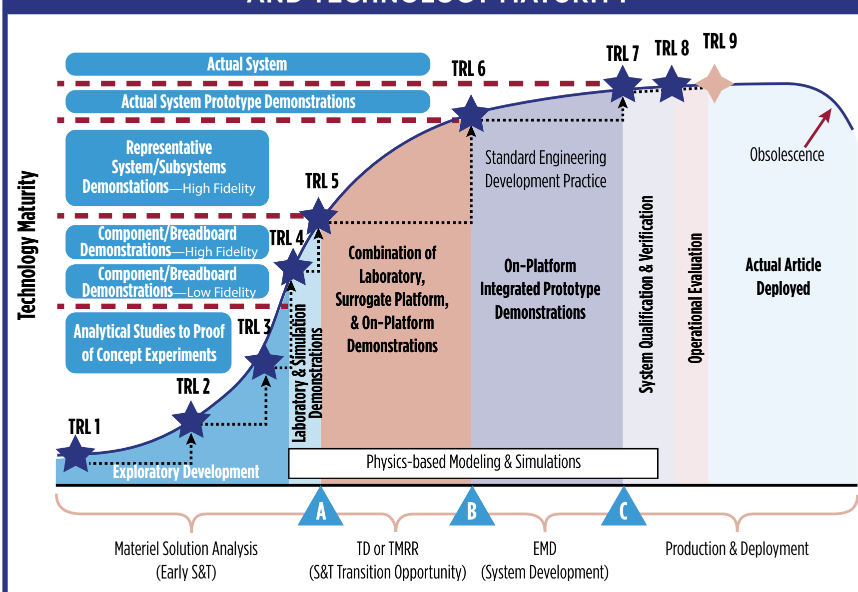
Criticality of Prototype Demonstrations on Technology Maturity

The term "maturity" or "technology maturity" refers to that period in which an enabling technology translates from instantiation of an idea to the realization of that idea's fullest potential. The product life cycle therefore transitions from early conceptual and technology development, through systems development (i.e., Developmental Test and Evaluation), operational test, production, market or user introduction, and finally, to disposal or recycle.

Maturity is a relative term that is applied based on comparison to a predefined end state. When discussing the readiness to enter system development, a technology that has not achieved TRL 6 is considered "immature." According to DoD (DoD, n.d.; Taylor, 2007) and Public Law (NDAA, 2006, 2008), technologies that are TRL 6 or better are considered as meeting the minimum maturity level acceptable to enter system development (i.e., EMD) at Milestone B. When considering a production decision at Milestone C, DoD best practice requires technologies to be at least TRL 7 to be considered mature enough to enter a production decision. A similar relationship applies when considering readiness for deployment; those technologies not yet TRL 8 (i.e., fully qualified, specification-compliant, and ready to enter operational test) would not be considered mature enough to enter the capstone Operational Evaluation (OPEVAL). Although GAO and DoD agree that any critical technology less than TRL 6 is considered "immature," GAO recommends that TRL 7, not TRL 6, is the appropriate level of technology maturity when entering product development (i.e., EMD or GAO Knowledge Point #2). GAO refers to critical technologies at TRL 6 as "approaching or nearing maturity." DoD considers TRL 9 as the level when a critical technology can be considered fully mature (i.e., when the system is considered suitable and effective by the user and deployed to field). GAO, on the other hand, considers critical technologies as "mature or fully mature" at TRL 7 when a production decision at Milestone C is required (i.e., GAO Knowledge Point #3; GAO, 2006a, p. 132).

Figure 2 associates the level of prototype and demonstrations, the venue for those demonstrations, and the technology maturity achieved as delineated by assigned TRLs to the applicable dimension of the DoD acquisition life cycle. The diagram shows that as Science and Technology (S&T) progresses from early exploratory development (i.e., basic principles, analytical studies, and early experimentation) to the formulation and test of component/breadboard prototypes in a low-fidelity laboratory environment, the product performance (i.e., demonstrated technology maturity) curve exhibits a gradual-to-exponential growth (TRL 1 to TRL 4). After entering Milestone A (i.e., Technology Maturation and Risk

FIGURE 2. LEVEL OF PROTOTYPE DEMONSTRATIONS, VENUE, AND TECHNOLOGY MATURITY



Note. EMD = Engineering and Manufacturing Development; TD = Technology Development; TMRR = Technology Maturation and Risk Reduction; TRL = Technology Readiness Level; S&T = Science and Technology.

Reduction phase), the curvature becomes less steep over an extended period of technology development as competitive prototype solutions are used to demonstrate critical technologies in a relevant environment (i.e., TRL 6). Upon achieving a TRL 6 level of maturity, a more gradual inclining plateau results for the duration of EMD. This flatter profile indicates a lower technological risk exists (i.e., related to technology maturity) and a representative system prototype or model of the end-state product has been achieved. During EMD, there should be no more reliance on S&T; only standard engineering developmental test and evaluation should be applied both to finish product design and build/test a production representative prototype (i.e., engineering development model) prior to Milestone C. After the actual system has been fielded and the technology eventually approaches end-of-life, the tail of the flattened S-curve dips, reflecting technology aging as well as a degradation in both system reliability and supportability.

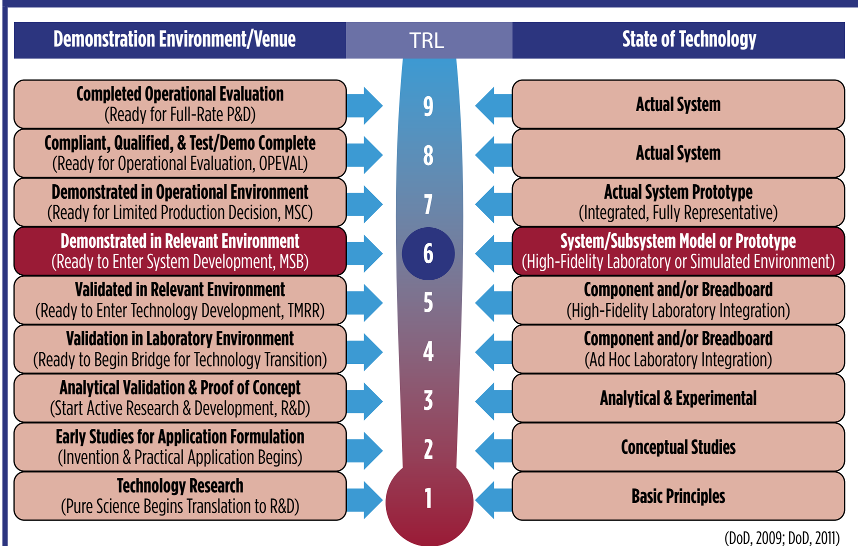
As shown in Figure 2, the S-curve shape represents a generic depiction of increasing technology maturity and product performance over time while progressing through the acquisition life cycle. Several analogies have been theorized relating technology maturity with the shape and phenomenon of an S-curve (MITRE, n. d.; Nolte, 2008). Although the shape of the curve implies a changing rate of improving maturity or product utility consistent with increasing levels of integrated prototype demonstrations and development progress, the overlaid TRL mapping shown in the figure should be interpreted as discrete threshold attainment points where increasing levels of technology maturity can be claimed. TRL values are assigned only as integer values (i.e., DoD does not recognize a readiness level fraction). Only when enough aggregate demonstration evidence of technology maturation has been collected can the Technology Readiness Assessment (TRA) independent review panel substantiate assignment of the next integer TRL value. The TRL definitions, demonstration criteria, and TRL values, as overlaid onto the S-curve and shown in Figure 2, are consistent with DoD guidance and policy (DoD, n.d; DoD, 2011).

Key Aspects of Prototype Demonstrations

The applicable venues for the demonstration of a prototype depend on the level of information required, complexity and integration level of the prototype, relevant environment in which the prototype must operate, performance expectations, and the technology maturity required at the associated stage within the DoD acquisition life cycle. Considerations of potential relevant environments for which a critical technology would need to survive and meet operational performance would include physical, logical, data, security, and user. The relevant environment is characterized by the critical technology application and its operational performance expectations while under worst-case, mission-relatable conditions.

A Critical Technology Element (CTE) represents an enabling technology that is deemed critical to meet operational performance of the system to be acquired and is also (a) a technology or application of a technology that is considered either new or novel, or (b) represents an area that poses

FIGURE 3. TECHNOLOGY READINESS LEVEL MAPPING TO PROTOTYPE DEMONSTRATION ATTRIBUTES



Note. EMD = Engineering and Manufacturing Development; MSC = Milestone C; MSB = Milestone B; OPEVAL = Operational Evaluation; P&D = Production & Deployment; R&D = Research & Development; TMRR = Technology Maturation & Risk Reduction.

a significant technological risk during product development (i.e., EMD) (DoD, n.d.; DoD, 2009). A TRA is conducted using an independent review panel to reconcile program CTEs and associate TRLs based on the level and quality of integrated prototype demonstrations accomplished.

Figure 3 provides a mapping of TRL descriptions and definitions to prototype demonstration environment and venue, level of technology, and expected attainment across the DAMS timeline.

Conceptual Framework

For this study, a research conceptual framework was established to examine the effects that system prototype demonstrations, when applied early in the systems engineering acquisition life cycle, would have on reducing technology risk for system development and production of U.S. military weapon systems. Since the approach leverages event-driven knowledge points (e.g., design reviews) consistent with standard systems engineering practice, the framework, as applied, can be tailored to accommodate other agency or industry product life cycles. The DAMS is a disciplined systems engineering, event-based framework in which acquisition programs proceed through a series of milestone decision reviews for authorization to enter subsequent life-cycle phases of the weapon systems acquisition process (DoD, 2013). Relationships were examined between key variables related to technology maturity, design maturity, and their corresponding impact on program performance.

The DAMS provided the rigorous structure necessary to collect and analyze descriptive statistics on independent variable constituents representing technology and design maturity, as well as on program performance dependent variables (i.e., cost, schedule, and product cycle time). Today's prevailing best practices endorse the use of system prototype demonstrations as a major contributor to true risk reduction before entering system development (Carter, 2010; Kendall, 2012; Young, 2007). In fact, DoD's expectations/assumptions now encompass realization of not only reduced program cost and schedule growth, but shorter product cycle time to the warfighter. The following questions were used to examine the validity of these assumptions:

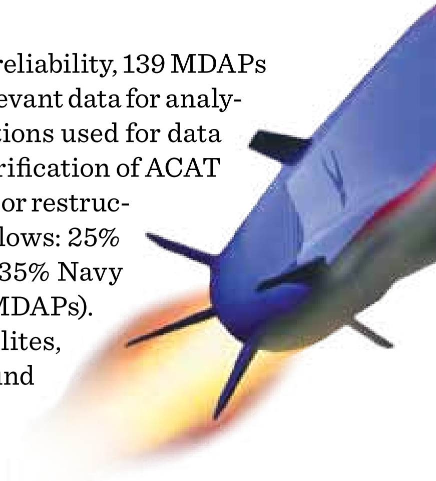
- Do technology development (i.e., pre-EMD) system prototype demonstrations provide a positive return on investment for weapon systems development?
- Do technology development system prototype demonstrations impacting technology maturity improve weapon systems development program performance?

- Do technology development system prototype demonstrations have a positive impact on achieving weapon systems design maturity?

Research Population and Sampling Description

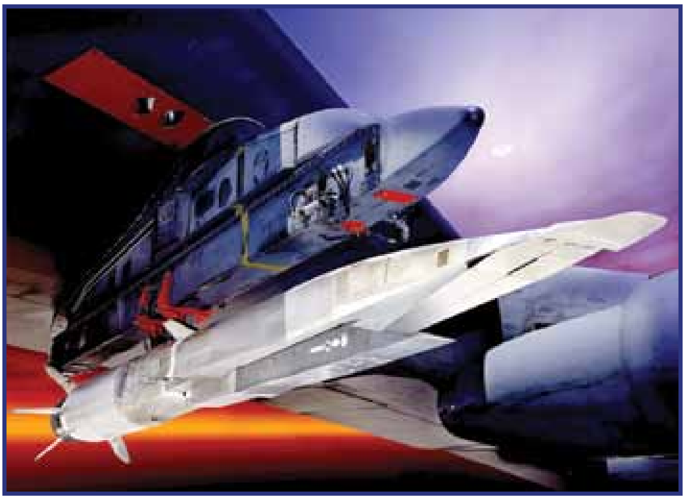
The research population, consisting of DoD MDAP portfolios ranging from FY 2002 through FY 2012, were designated Acquisition Category I (ACAT-I) since they were projected to exceed threshold FY 2000 constant dollars criteria for either Research, Development, Test and Evaluation ($365 million) or Procurement ($2.19 billion) (DoD, 2000, 2008). The latest interim DoDI 5000.02 (DoD, 2013) modified the ACAT-I designation criteria to be relative to FY 2014 constant dollars for subsequently established MDAPs. A mixed-methods research approach was used to collect and analyze historical program performance data and findings from available and relevant literary sources. Data collection was focused primarily on MDAPs that were part of the annually published GAO assessments for selected major weapon systems programs. These reports, dating from 2003 to 2013, represent limited case study, knowledge-based program performance assessments that were provided to the United States Congress. The actual data contained within these published reports are mostly reflective of the previous year's program performance, therefore representing MDAP portfolios spanning from 2002 to 2012. MDAP cost, schedule, and performance data were also collected from annual DoD SARs, which are submitted in conjunction with the President's Budget. The research data population consisted solely of MDAPs and did not include Major Automated Information Systems, or ACAT-IA programs.

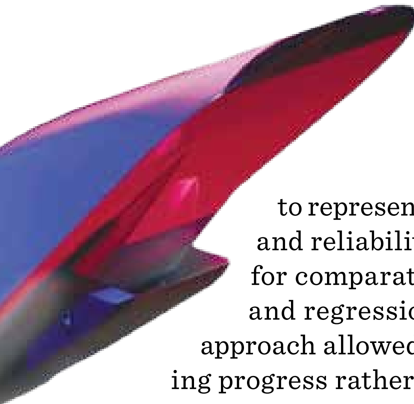
> ***"Considerations of potential relevant environments for which a critical technology would need to survive and meet operational performance would include physical, logical, data, security, and user."***



After initial data cleansing to ensure validity and reliability, 139 MDAPs were determined to contain enough usable and relevant data for analysis of key research factors of interest. Considerations used for data purification included adequacy of sample size, verification of ACAT assignment, and noting if programs were canceled or restructured. The research population spread was as follows: 25% Air Force (34 MDAPs), 23% Army (32 MDAPs), 35% Navy and Marines (49 MDAPs), and 17% DoD Joint (24 MDAPs). Product types included aircraft, helicopters, satellites, ships, submarines, ship/ground vehicles, ship/ground stations, sensors and electronic warfare systems, missiles, weapons and munitions, core electronics, and unmanned air vehicles. Hypothesis testing was limited to those MDAPs that were in or completed EMD. This final cleansed population of 117 MDAPs from which valid samples were empirically analyzed included 70 MDAPs that used system prototype demonstrations before entering EMD, and 47 programs that did not.

The MDAP data collected included available initial program baseline dates for systems engineering technical reviews and key decision points along the program acquisition timeline. Planned reviews were compared to actual event dates, and a percentage deviation was calculated





to represent either schedule reduction or growth. Data validity and reliability for factors and their constituents were assured for comparative analysis of descriptive statistics, correlation, and regression by using percentage deviation from plan. This approach allowed for findings to be explained by systems engineering progress rather than biased by other potential factors associated with the uniqueness of product type. Care was taken to compare only completed events so as not to skew the empirical analysis results with projected accomplishments.

General Introduction to Findings

A primary assumption in determining which programs applied system prototype demonstrations prior to entering EMD was the fact that all CTEs need to have achieved TRL 6. Any program that conducted a TRA and identified CTEs would have shown evidence that at least TRL 6 was achieved by Milestone B, therefore validating that a system-level demonstration had occurred; otherwise, the Milestone Decision Authority would not have been able to certify compliance with Title 10 U.S.C. § 2366 (NDAA, 2006). All programs after the 2006 legislation would meet this criteria with certainty. Programs that conducted TRAs post-2001, and before the 2006 legislation, would also apply given the need to be consistent with then-existing DoD 5000.02 policy (DoD, 2000) to perform technology maturity assessments through the application of TRLs and adherence to subsequent Office of the Secretary of Defense initial TRA deskbook guidance published in 2003 (DoD, 2003). MDAPs with acquisition strategy that included either a Demonstration and Validation phase or Technology Demonstration (TD) phase were also counted. These would correspond to MDAPs that held a Milestone A event (or analogous Milestone I event). Also included were those older MDAPs that employed Fly-Before-Buy or acknowledged system-level demonstrations that were still part of the active DoD portfolio in 2002, and therefore were reported by GAO and within the relevant data collection window of this research data population.

MDAPs that were counted as not using pre-EMD system prototype demonstrations were those that were initiated at or post-system development start (i.e., Milestone B or analogous Milestone II event). MDAPs that entered the DAMS at production (i.e., Milestone C or analogous

Milestone IIIA event) were not counted since the acquisition strategy likely did not include development activity, and therefore only accepted fully mature technologies into production.

Results and Findings

Linear Relationships Between Key Factor Constituents

To assess the strength and direction of any linear relationships, a Pearson correlation analysis was completed for research factor constituents associated with MDAPs using system prototype demonstrations to assess the strength and direction of any linear relationships. The impact that system prototype demonstrations have on technology maturity (e.g., TD span and technology readiness) was examined for any relationships with design maturity (e.g., percent drawings released by Critical Design Review [CDR] and percent schedule change to CDR) and program performance (e.g., cost and schedule growth).

The Pearson coefficient is based on the method of covariance and ranges from +1 to -1, where a value equivalent to zero (0) indicates no correlation between variables. As shown by the sign of the coefficient, the direction of the linear fit represents a positive or negative relationship (Laerd Statistics, 2013). Table 1 summarizes constituent relationships for MDAPs that used system prototype demonstrations prior to EMD. All constituent pairs shown in Table 1 met a 0.10 or higher level of significance (i.e., establishing that a relationship exists).

Four constituent pairs (AB2, AB3, AB4, and AB5) indicated a high degree of association (i.e., strong correlation) and are characterized as follows: (a) any change in the number of CTEs taken into system development will realize a corresponding change in the time required for TD; and (b) any change in the duration of time required for TD will have a similar schedule impact to system development (i.e., EMD phase), as well as an opposite impact on percent acquisition cost growth. Therefore, the greater the number of immature CTEs necessary to meet a capability gap, the longer the TD phase will be to reduce technology risk prior to entering system development. Additionally, given the increased leverage of enhancing emergent technologies, the EMD phase will likely be longer to accommodate additional systems integration and test. The extended TD phase would, with other factors not considered, contribute to a reduction in acquisition cost growth. Additionally, two constituent pairs (AB1 and AB6) were identified as having a moderate degree of association and

TABLE 1. PEARSON PRODUCT-MOMENT CORRELATION ANALYSIS OF KEY CONSTITUENTS
(MDAPs with System Prototype Demonstrations Prior to EMD)

Pair Identifier	Factor Constituent Pairs		Pearson Coefficient	Level of Significance	Pair Relationship
	(A)	(B)			
AB1	% Acquisition Cost Growth, Since First Full Estimate (GAO, 2012)	EMD Span	-0.437	0.05	Moderate
AB2	% Acquisition Cost Growth, Since First Full Estimate (GAO, 2012)	TD Span	-0.710	0.01	Strong
AB3	% Acquisition Cost Growth, 2006-2011 (GAO, 2012)	TD Span	-0.533	0.10	Strong
AB4	EMD Span	TD Span	0.740	0.01	Strong
AB5	Number of CTEs	TD Span	0.606	0.05	Strong
AB6	TD Span	% Acquisition Cycle Time Growth	-0.445	0.10	Moderate

Note. CTE = Critical Technology Element; EMD = Engineering and Manufacturing Development; IOC = Initial Operational Capability; TD = Technology Development.

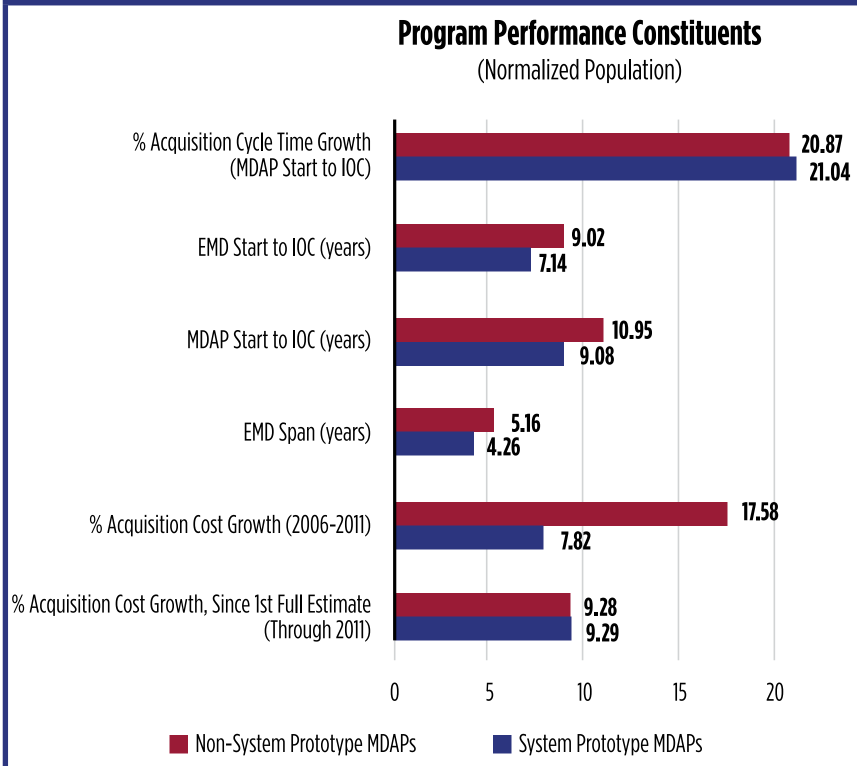
are interpreted as follows: (a) with a change to EMD span time, there is a corresponding opposite change in acquisition cost growth relative to First Full Estimates; and (b) with a change in TD span time, there is a corresponding opposite change in acquisition cycle time growth. Therefore, with longer TD spans to accommodate increased risk mitigation and maturation activities due to increased number of CTEs, the overall acquisition cycle time can be reduced as a result. Similarly, with longer EMD span times likely to mitigate complexities associated with standard engineering development and complex integration, the percentage of acquisition cost growth can be reduced. Due to direct relationships among key constituent pairs, the Pearson correlation analysis indicates that high potential exists for a positive effect on program performance when implementing effective risk reduction through the use of system prototype demonstrations.

System Prototype Demonstrations Provide a Positive Return-on-Investment

With the exception of percentage acquisition cost growth since the First Full Estimates and percentage cycle time growth from program start to IOC, Figure 4 shows that the remaining program performance factor constituents show a modest improvement when employing system prototype demonstrations before entering system development. MDAPs that leveraged system prototype demonstrations prior to EMD realized a mean reduction in acquisition cost growth (2006 to 2011) by as much as 125% over those that did not, i.e., $[(17.58-7.82)/7.82] \cdot 100 = 125\%$. Although percentage cycle time growth was relatively equal, with the addition of a TD phase (i.e., system prototype demonstrations), the net cycle time to the warfighter from both program start and EMD start to IOC was reduced by 17% and 21%, respectively, relative to MDAPs that did not use system prototype demonstrations. The average TD phase span for a sample of 41 MDAPs equated to 3.18 years. The noted improvement in percentage acquisition cost growth measured from 2006 to 2011, as compared to no improvement when measured against First Full Estimates (through 2011), coincides with the 2006 Public Law (NDAA, 2006) decree that all immature critical technologies are required to be demonstrated in a relevant environment (i.e., TRL 6) prior to receiving approval to enter EMD.

Although the empirical analysis, as depicted in Figure 4, shows a minimal difference in percentage cycle time growth from program start to IOC for those MDAPs that did and did not use system prototype

FIGURE 4. COMPARISON OF MDAP PERFORMANCE KEY CONSTITUENTS
(With & Without System Prototype Demonstrations Prior to EMD)



demonstrations before EMD, the development cycle time required to IOC or from program start to IOC is on the average 1.9 years shorter for MDAPs using prototypes. Coincidentally, programs that used system prototype demonstrations had a 9.8% lower mean total acquisition cost growth when assessed using 2006 to 2011 data.

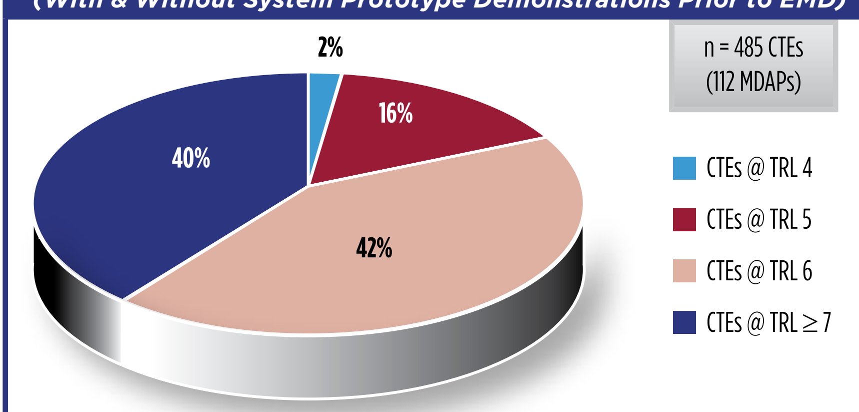
When comparing available MDAP performance data that are coincident with the implementation of key DoD policy and congressional legislation, the benefits gained from pre-EMD system prototype demonstrations are amplified. Since policy was introduced by DoD in 2001 to adopt TRLs and implement a TRA-like process, a 23% reduction in mean total acquisition cost growth, relative to First Full Estimates (through 2011), has been realized (i.e., 26.2% cost growth prior to July 2001 versus 3.64% cost growth post-July 2001). Subsequently, with the enactment of the

NDAA of 2006 establishing a TRL 6 certification requirement for all immature technologies prior to entering EMD, a further reduction of 1.63% is observed (i.e., 3.64% cost growth post-July 2001 versus 2.1% cost growth post-January 2006). Data were binned based on when the MDAP EMD start date occurred relative to the official instantiation of the policy or legislation.

System Prototype Demonstrations Increase Technology Maturity

Technology maturity at Milestone B is a significant factor since it gauges the level of technology risk carried forward into system development. Post-January 2006, the NDAA of 2006 ensured that a minimum acceptable TRL would need to be achieved before awarding a development contract. Just as important, but not currently regulated by DoD or legislated by Congress, is whether there should be a best practice or policy on the total number of CTEs considered reasonable for an MDAP to adequately manage in system development. The number of CTEs could imply adequacy of requirements and extent of system design complexity required to meet operational needs. The data show that when the cycle time from EMD start to IOC increases, there is a corresponding increase in the number of CTEs that were carried into EMD. This fact, coupled with the knowledge that EMD span increases with shorter TD spans, implies that the greater the number of immature critical technologies

FIGURE 5. PERCENT CRITICAL TECHNOLOGY ELEMENTS PER TRL RATING AT DEVELOPMENT START (I.E., MILESTONE B)
(With & Without System Prototype Demonstrations Prior to EMD)



introduced into EMD, the greater the technology risk transferred to system development, and hence increased threat for increased cost and schedule growth (i.e., reduced buying power).

Figure 5 represents the total number of CTEs reported by MDAPs at entry to system development (i.e., Milestone B), independent of whether or not system prototype demonstrations were used prior to Milestone-B.

The data show 77.7% of the MDAPs at Milestone B reported CTEs at TRL 6 or greater (47.3% at TRL 6 and 30.4% at ≥ TRL 7). The remaining 22.4% of the MDAPs entered system development with CTEs less than TRL 6. Up until January 2006, DoD was receptive to accepting and managing technology risk in EMD based on the establishment of a timely and viable risk management plan. The 25 MDAPs that did not meet minimum technology maturity requirements before entering system development held Milestone B prior to TRL 6 becoming statutory law in 2006 (NDAA, 2006). The mean number of CTEs entering system development is four for both system prototype and non-system prototype demonstration programs. MDAPs using system prototype demonstrations have shown a 12% reduction in the number of programs entering EMD with three to five CTEs. On the other hand, the data also show a 4.1% increase in the willingness of MDAPs using early system prototypes to carry 6 to 10 CTEs into EMD, and correspondingly a 2.2% increase for those carrying greater than 10 CTEs.

System Prototype Demonstrations Increase Systems Design Maturity

A measure of design maturity is the percentage of engineering drawings available to be released to manufacturing at both CDR and by the Milestone C production decision point. For MDAPs sampled (n = 50), independent as to whether system prototype demonstrations were employed prior to EMD, only 48% of the MDAPs met DoD best practice goals (DoD, n.d; DoD, 2011) of 75% to 90% engineering drawings complete and releasable to manufacturing by CDR. Correspondingly, only 34% of MDAPs met the GAO best practice goal (GAO, 2013) of at least 90% by CDR. The mean percentage engineering drawings released to manufacturing by CDR for MDAPs that used system prototype demonstrations prior to EMD is significantly greater than those that did not (i.e., 73.7% for MDAPs using prototypes versus 51.25% for MDAPs not using prototypes). Although for CDR there is a notable 22.5% improvement in completion of engineering drawings for MDAPs using system prototype demonstrations prior to EMD, this mark remains slightly short of the DoD best practice goal and 16.3% short of GAO's knowledge point best practice goal. The mean percentage schedule change to CDR (plan versus actual) for those MDAPs that conducted system prototype demonstrations prior to EMD is 1.84%—significantly less than the 12.45% realized for those programs that did not.

Conclusions

The following quote (Farrell, 2011) appropriately characterizes today's environment and the need to apply systems engineering tools smartly, such as system prototype demonstrations, to achieve early and effective risk reduction:

> "Gentleman, we have run out of money. Now we have to think."
>
> —Sir Winston Churchill

With the harsh realities of today's economics and the need to implement true risk reduction activities through sound systems engineering practice, DoD is looking to leverage the knowledge gained through system prototype demonstrations to reduce technical risk and provide state-of-the-art weapon systems to the warfighter sooner—and at a decidedly reduced acquisition cost.

The application of system prototype demonstrations to improve technology maturity and accelerate design maturity, as evidenced by the findings of this study, do indeed have a profound positive influence on the

> ***The knowledge gained by this study can help the government, in collaboration with industry, formulate more effective risk mitigation strategy for the transition of influential enabling technologies into system development such that overall cycle time to the warfighter can be reduced.***

outcome of weapon systems development performance. Data have also shown that with the implementation of key policy and legislation to reinforce the need to perform system-level prototype demonstrations prior to entering system development, MDAP total acquisition cost growth can be further reduced. Some key findings follow:

- The greater the number of CTEs entering system development (i.e., EMD), the longer it will take to complete the preceding TD phase. Therefore, it can also be interpreted that the more mature the technology solution to fill a capability gap (i.e., leverage of proven technology), the less the dependence on TD and the shorter the cycle-time to deliver IOC to the warfighter.

- Increased focus and time invested during TD to maturate technology solutions and reduce system development risk will have a positive contribution to reducing both acquisition cost growth and overall product cycle time to the warfighter.

- Although all MDAP CTEs in EMD achieved at least TRL 6 by Milestone B since 2006, the average number of CTEs carried into EMD remained unchanged. Assuming the MDAP is not a production entry (i.e., Milestone C) or rapid deployment acquisition, researchers found no evidence to suggest any policy or directives that would minimize the actual number of CTEs acceptable for entry into EMD.

- The average percent of manufacturing quality engineering drawings available by CDR is 22% higher for MDAPs that used system prototype demonstrations prior to EMD. There was insufficient evidence to link the percentage of engineering drawings completed to the amount of CTEs entering EMD.

- MDAPs with system prototype demonstrations that exercised a TD phase realized reduced product cycle time of 17% (1.88 years) from program start to IOC, and 21% (1.87 years) for EMD start to IOC. Based on a sampling of 41 MDAPs, the average span time for a TD phase has been 3.18 years.

The knowledge gained by this study can help the government, in collaboration with industry, formulate more effective risk-mitigation strategy for the transition of influential enabling technologies into system development such that overall cycle time to the warfighter can be reduced.

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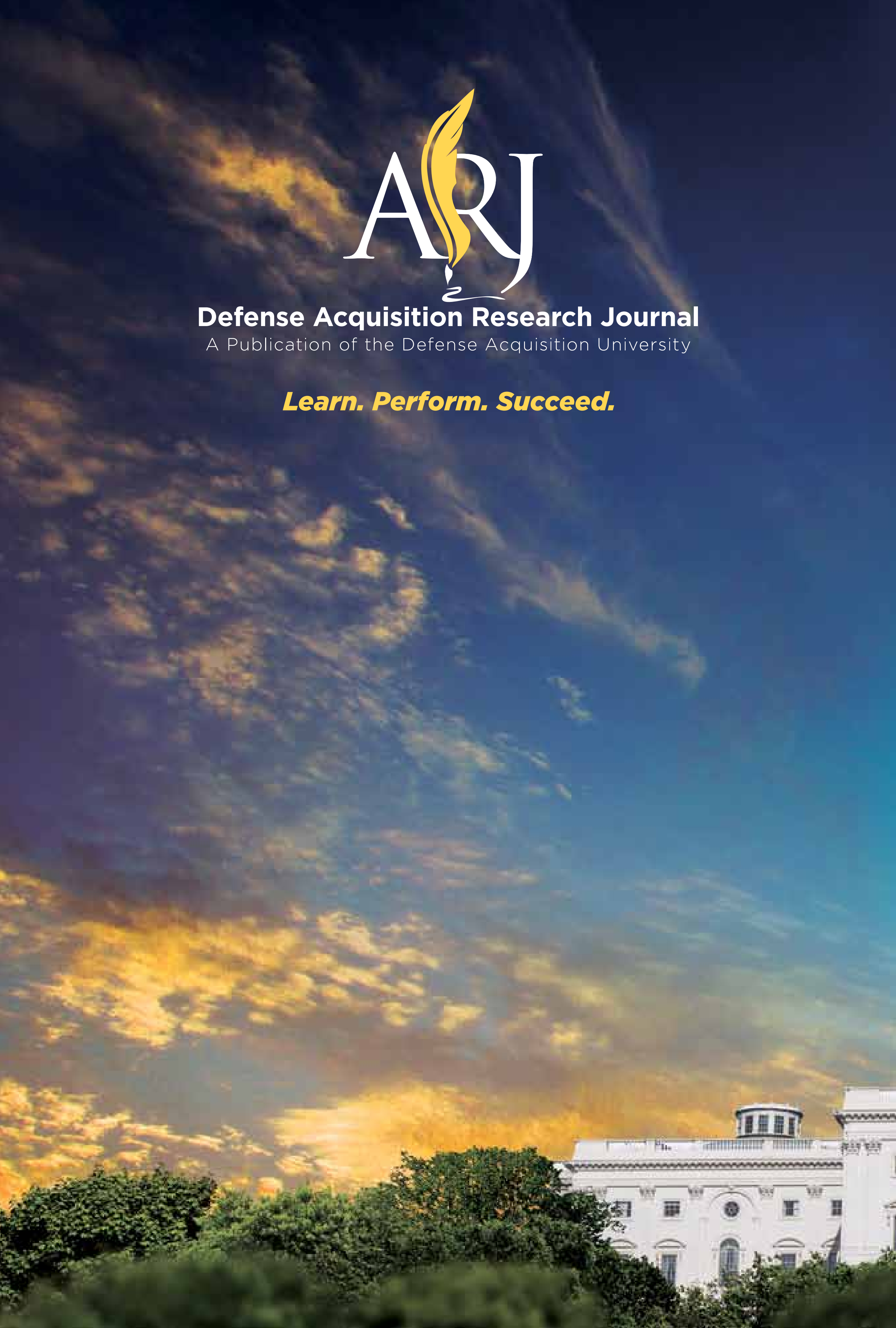

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