Engineering the Acquisition Process: Better Value Through Mechanism Design

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Abstract

As both the regulator and the only buyer in a market that measures over $500 billion a year in acquisitions, the Department of Defense has tremendous leverage but does not make much use of it. Limited competition in the prime contractor market results in higher prices and lower quantities purchased. There have been some recent strides to achieve better value, but much more can be done if the government will pursue strategic approaches. In this paper, we consider the use of mechanism design to achieve better value.

Introduction

In 149 B.C., the military leader Kong Ming and a few of his bodyguards had retreated after defeat in battle to the city of Yangping, China. Fleeing an army of 50,000 soldiers. Ming opened the gates to the city, made all the guards hide, and removed all battle flags from the city walls. He then placidly sat in one of the towers, in unobstructed view of the approaching army, playing his lute. Suspecting a trap, the large army quickly departed. The moral of the story is that a little strategic thinking can deliver big results. (Raeburn and Zollman 2016) The study of these kinds of conflicts emerged in the 20th century into game theory, an important field of economics. You may be familiar with the strategic concept of mutually assured destruction where both the Soviet Union and the United States were (and may still be) willing to threaten the ultimate destruction of the other if attacked. The intent of such a strategy is to dissuade the other side from launching a nuclear attack. This strategy proved to be effective in preventing the Cold War from turning into a thermonuclear hot one. In this paper, we leverage game theory to help resolve an enduring problem that the United States government has been trying to solve since the end of World War II, which is the high cost of government weapon and aerospace systems.

The Department of Defense has an annual budget greater than $500 billion. Despite being both the regulator and the only buyer in this huge market, defense acquisition is plagued with cost overruns - average cost growth for DoD development programs has consistently been greater than 50% since the 1970s! In addition to the problem of cost overruns, the government pays high prices. In some cases, the government pays exorbitant costs for simple items. In 1985, one headline was “Pentagon pays $640.09 per toilet cover, gives new meaning to ‘throne.’” (Deseret News 1985) As recently as last year, the price to the government for a new toilet cover was an outrageous $10,000. (Weisberger 2018) There have been multiple initiatives to achieve better buying power, but these policies have not fully leveraged either the government's regulatory oversight or its monopsony power. As noted in one report, the government has been “spending more and getting less.” (Walker 2002)

We review a recent attempt to solve this issue, particularly the Better Buying Power paradigm implemented in the Department of Defense. The primary structural challenge to this paradigm is the dearth of competition among prime contractors. For some defense products, the prime contractor has a monopoly. This is typically the case in production. We examine the monopsonistic aspects of government acquisition and the monopolistic and oligopolistic aspects of the prime contractor market.

We then turn to game theory and show how these concepts can be leveraged to compensate for the lack of competition, just like Kong Ming defeated an army of 50,000 without fighting. We make use of the concept of mechanism design as a means for the government to set the terms for acquisition that is more beneficial for the taxpayer and the security of the nation. Mechanism design turns game theory on its head by designing games that achieve a desired goal. It has been successfully used for auctioning the radio spectrum and improving the market for kidney donors and recipients. In this paper, we show how this powerful concept can be used in production acquisition to eliminate the deadweight loss due to monopoly to achieve both lower prices and higher quantities.

As an aside, throughout the paper the authors provide real-world acquisition examples from their experiences. However, to protect the guilty, we do not mention names of the program managers or their programs.

Better Buying Power and Will Cost-Should Cost

Cost growth has been an endemic phenomenon since the beginning of the modern defense industry following World War II. Over 80% of NASA and Department of Defense programs experience some cost growth, and the average cost growth during the development phase is approximately 50%. Norm Augustine, who had experience as both a defense contractor CEO and a government official, observed that the average cost growth for government development programs was 52%. He stated that if you were given the initial projection of cost for development, you only need to multiply it by 1.52 to get the expected actual cost, which he termed the “Las Vegas Factor of Development Program Planning.” (Augustine 1983) More recently, cost growth studies for DoD and NASA programs have found that the average cost growth of development programs is still 50% or more. (Smart 2012, Prince and Smart 2018) The government has also historically paid high costs for weapon system compared to similar items that are available commercially, such as the $10,000 toilet seat cover we mentioned earlier. Because of these issues, the government has enacted a series of initiatives to attempt to develop realistic early estimates and find ways to cut costs from program inception.

The most recent of these initiatives was spearheaded by former Under Secretary of Defense for Acquisition, Technology, and Logistics (USD ATL) in late 2010 who termed this strategy Better Buying Power. Better Buying Power is an attempt to reform acquisition by incentivizing from within the system through a groundwork of best practices and standardized policies.

Prior to the implementation of the Better Buying Power directive, the standard approach to acquisition reform was driven through external incentives that wavered in accordance with the temperament of decision makers on Capitol Hill. The implementation of the first iteration internalized DoD acquisition incentives through five major initiatives:

- Target cost savings and control cost growth
- Provide incentives for industry innovation and productivity
- Promote competition
- Improve the skills of the acquisition workforce
- Reduce non-productive process and cut bureaucracy

(Source: Kendall 2010)

Our discussion will focus on the first of these, which was implemented by using Will Cost/Should Cost management. Will Cost is defined as reasonable extrapolations from historical cost data. Should Cost is defined as Will Cost minus achievable efficiencies. Should Cost encourages program managers to find ways to accomplish more without spending more.

To illustrate the concepts of Will Cost and Should Cost, consider the following example. When procuring production units with a budget equal to $420 million a year, the historical cost estimate indicates that the program can afford 30 units at $14 million each. However, by entering into a multi-year agreement to buy the same number of units each year for five years, the prime contractor can cut costs by buying critical components in bulk. In return for the security of five years of production versus only a one-year contract, the contractor will agree to pass along some of these savings to the government. The result is that the units now cost $12 million each, so that the government can now afford 35 units each year ($12*35 = $420), without an increase in the production budget. Note that the program manager did not have to give up the savings outside the program but was able to use the savings to buy more units. This is a key feature of Will Cost/Should Cost management. If the program manager must give up savings and take a budget cut, he or she will have an incentive to not find Should Cost savings. The idea is to budget to the Will Cost but manage to the Should Cost. The inclusion of the program manager in the process makes this an internal process. The Department of Defense claims this makes Better Buying Power more effective than previous cost savings initiatives since they were externally imposed on programs. (Department of Defense 2016)

While Should Cost is about achieving savings, it is not a “management challenge” to arbitrarily cut costs. It is also not taking on more risk; for example, moving from a budget at a 70% confidence level to one that is at a 30% confidence level. Should Cost also does not involve cutting scope or requirements.

There have been several notable examples of cost savings achieved by Will Cost/Should Cost management. The Navy saved $298 million when it chose to utilize Fixed Price Incentives – Firm Target contracts with priced options to ensure reasonable prices while maintaining the industrial base. (USD ATL, 2013) The Army achieved 5% costs savings in the Stryker program by combining FY12 buys of 292 Double V-Hulls and 100 Nuclear Biochemical Reconnaissance vehicles into a single contract. (USD ATL 2013) The Air Force's F-22 System Program Office realized 15 percent savings during Increment 3.2A negotiations using Should Cost analysis. (USD ATL 2013) Other examples include the AIM-9X Active Optical Target Detector and the Guided Multiple Launch Rocket System. (DAU, 2013)

Other defense agencies have also achieved success with implementing Should Cost efficiencies. A recent example of Should Cost success is an interception production buy for the Terminal High Altitude Area Defense (THAAD) program. Prior to 2015, it was common practice at the Missile Defense Agency to procure interceptors via single-year contracts. In January 2015, THAAD decision makers saw an opportunity to take advantage of efficiencies from overlapping the contractual period-of-performance with the THAAD Combined Buy Production Contract. This overlap between fiscal year 2015 and fiscal year 2016 allowed for the incorporation of fiscal year 2016 interceptor purchases into the fiscal year 2015 proposal at a negotiated lower Average Unit Price (AUP), resulting in significant economies of scale. "Using the synergy buy approach, the THAAD Lots 7 and 8 Interceptor contract was awarded for a total quantity of 72 Interceptors, with an AUP savings of over $2.4M based on the Lots 7 and 8 stand alone cost estimate, and $1.1M savings per AUP compared to the Prior interceptor procurement for USG Lots 4, 5 and 6 referred to as Combined Buy negotiated price." (Crowe and Embrey 2016) These savings were achieved by combining lots using the THAAD Combined Buy Production Contract. These savings were then reinvested to enable the program to procure an additional 11 interceptors. For the first time in the history of the program, the AUP was less than $10 million and this approach was adopted for the fiscal year 2017 and fiscal year 2018 procurements.

While in retrospect this appears simple, implementing the synergy buy in THAAD was an uphill battle from start to finish. In the throes of programmatic chaos and churn, decision makers had to identify and consider the opportunity of multi-year procurements. Decision makers had to recognize the benefits of putting more money up front to save money later. The program also had to ensure that the one-year funds for the second fiscal year would be appropriated in the first quarter, so the contractor would be paid in a timely manner.

Will Cost/Should Cost management evolved from a lone requirement in 2010 to a core factor in acquisition reform in 2015 and now requires quarterly reviews by both the Defense Acquisition Executive and the Business Senior Integration Group. The introduction of an annual Should Cost and Innovation Award provides program leadership incentives to execute Should Cost management.

Despite some successes, Should Cost savings are difficult to implement. It is often easy to implement cost savings when measured by contract award values versus internal program office cost estimates. Cost typically grows from the initial contract value, often by a significant amount. Some of the savings cited earlier involve fixed-price contracts, which limits the amount of cost growth to a large extent. However, some of the savings that the Department of Defense is touting involves cost-plus contracts, in which case the savings may be more apparent than real. Another issue is that Should Cost initiatives often require more money up front, such as with the THAAD program example. Program offices rarely want to increase spending in the near term to save money longer term. A third issue with Should Cost management is that even though the budget is supposed to be set to the Will Cost estimate, decision makers have a temptation to budget to the lower estimate. In these cases, Should Cost estimates, rather than Will Cost estimates, become the basis for the budget cycle. When those should cost initiatives fall through, programs experience significant cost growth. In those cases, rather than designing in cost savings from the beginning, the program is being set up for cost growth.

The Department of Defense claims significant reductions in annual cost growth because of its implementation of Better Buying Power. Since its inception, this strategy has coincided with steep and steady declines in contract cost growth in the years following, dropping from approximately 9 percent in 2010 to 3 percent in 2015.

From 2013 to 2016, the Department of Defense published annual performance reports and in 2016 provided information on the five-year moving average of annual cost growth for major defense acquisition programs from 1985 to 2015. This is displayed as the dotted line in Figure 1.

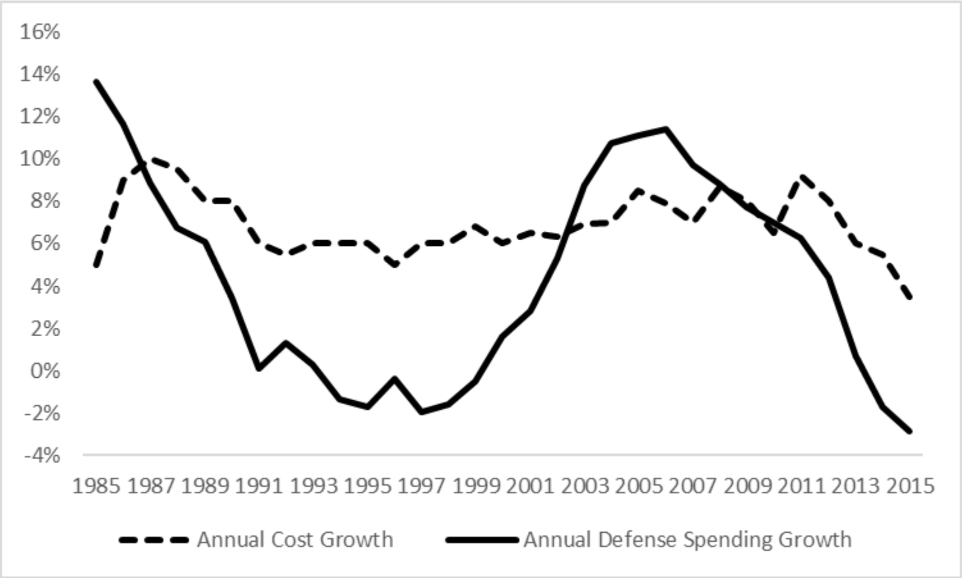


Figure 1. Cost Growth Fluctuations Compared with Changes in Annual Defense Spending (OMB 2016, Department of Defense 2016).

Annual cost growth has fluctuated between 5 and 10% annually but dropped to almost 3% in 2015. This is encouraging information. However, the swings in cost growth are highly correlated with the swings in the defense budget. The 5-year moving average of annual percentage changes in the annual defense budget is displayed as the solid line in Figure 1. The correlation between these two sets of values is 60%. When defense spending starts to slow, there is a great deal of focus on affordability, but that emphasis dissipates when the budget starts to increase again. The defense budget has recently increased by a large amount, so an increase in cost growth is also likely to return.

Another challenge is that the previous Presidential administration introduced and implemented the Better Buying Power initiative. With a change in administrations two years ago, there have been some significant changes to the Department of Defense organizational structure. The architect of the Better Buying Power strategy, Ashton Carter, was the Undersecretary of Defense for Acquisition, Technology, and Logistics. That job has recently been split in two, with one half dedicated to the acquisition of traditional military systems, and another that focuses on research and development. With these changes, Better Buying Power may soon become a legacy initiative. The new Undersecretary of Defense for Research and Engineering, Michael Griffin, is focusing on rapid prototyping to achieve efficiencies in cost and schedule.

One key limitation to Better Buying Power is that it is ad hoc. Cost savings ideas tailored to specific programs may achieve some savings, but it would be beneficial to also take a step back from the individual trees to look at the forest. For example, the consideration of a more overarching strategy that could result in even more savings beyond that facilitated through Better Buying Power.

In the experience of one of the authors, the use of Better Buying Power was focused primarily on competition and multi-year procurement. A key tenet is to "promote effective competition." (USD ATL 2015) However, there is not much competition in defense, aerospace, or in most other markets in the United States. (Tepper 2019) In the next section of this paper, we examine the limitations of competition in the defense market and its impact on prices.

Industrial Organization of Defense and Aerospace Contractors

In Economics 101, you learn about markets that have many sellers and many buyers. In this case of "pure competition," neither the buyers nor the sellers can influence the price of goods. Adam Smith's "invisible hand" ensures that there will be an equilibrium price reach where supply equals demand. In the real world, matters are typically more complicated. In the market for defense and space systems, there are a limited number of suppliers and only one buyer.

Government as Monopsony

The case when there is one buyer in a market is termed a monopsony. The economist Joan Robinson wrote about monopsonies from the perspective of monopolistic firms that have market power in the labor market. They are a monopsonist in hiring, which allows them to “pay workers less than the value of their output and keep more for themselves.” (Yueh 2018) Less attention has been paid to the monopsonist as a buyer of finished products.

The notion of a monolithic government as a single buyer is a simplifying assumption. For some products, there are multiple buyers. For example, with satellites, the National Reconnaissance Office, NASA, and the Air Force all procure satellites. For other markets, such as tanks and missiles, you can consider the Department of Defense to be the sole buyer, or in the case of tanks, you can limit that buyer to the Army. There are multiple parts of the government and multiple entities involved in the acquisition of weapon systems, including the service or agency that is the direct procuring agency, but also there is involvement by: the Office of the Secretary of Defense and various bureaucratic agencies within this organization, such as the office of Cost Assessment and Performance Evaluation that provides independent cost estimates and assessments for major defense programs; Congress, which ultimately controls funding and adds to programs and cuts program funding at its discretion; and the office of the President of the United States, who is the Commander in Chief of the Armed Services and submits the annual budget to Congress, including that for defense and space systems.

Even considered as a monopsonist, the government is a relatively weak one. Department of Defense senior executives have admitted to one of the authors that the government does not fully leverage its negotiating power. One potential consequence of the monoposonist is that it can push down prices but only in the relative short-run, such as at the beginning of a project. The government program managers and other leadership are typically quick to believe a low estimate from a contractor before they believe a higher, more realistic estimate produced by one of their own cost estimators. In the longer-term, by the time a project is complete, the contractor cannot lose money and stay in business. This explains why, in a competition, the contractor bids low, but cost then grows during development so that the contractor makes money by the project’s end. Indeed, this dynamic of increasing costs from a proposal to the completion helps explains the systemic cost growth experienced by NASA and defense programs. As these are typically cost-plus contracts, the contractor suffers little to no detriment by setting unrealistically low bids. As Norm Augustine wrote in the early 1980s, “Bid ‘em low, watch ‘em grow.” (Augustine 1983) One of the authors knows a consultant whose primary business is to teach defense and NASA contractors how to bid lower than they believe a project will cost to win the work.

The cost of development is not as big of a concern for the prime contractors, since the real money is in the production and operations and sustainment phases. In the 1950s, the President of North American Aviation noted “there is an incentive to bid low on development contracts in order to win both the development and production work,” and “assumptions ultimately drive the projections for design requirements and costs; and assumptions are subject to optimistic bias.” (Lofgren 2017) As a concrete example, for a project in which three contractors developed a program through the completion of a full set of two dozen prototypes, with the winner of the production contract selected among the three, the winning contractor lost millions of dollars on the prototypes, but more than made it up by winning the production contract for a program for which the government will procure tens of thousands of units.

Here is a reason for cost growth from the producer side – the notion that a development contract competition is basically an auction for the monopoly rights to produce and operate the system. This is because the bulk of the life-cycle cost for a large program is in operations, followed by production. Development is only a small part of the total, and accounts for a small fraction of the time of the total life-cycle for most Department of Defense programs. Thus, the development work can be considered a buy-in for the real payoff in productions and sustainment. See Figure 2.

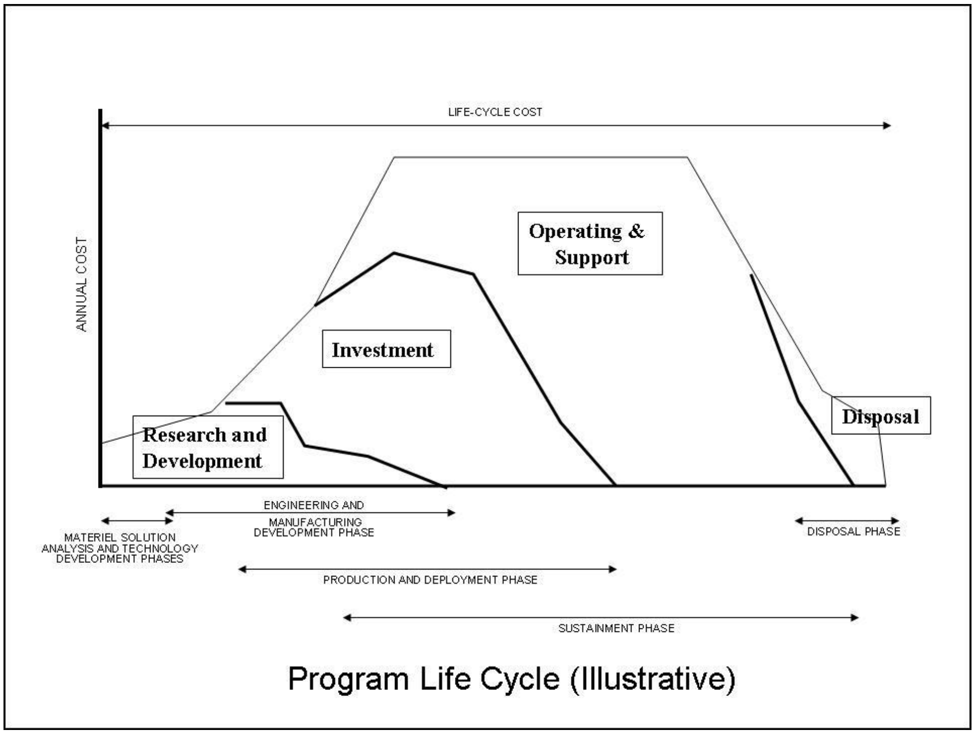


Figure 2. Program Life Cycle and the Tip of the Iceberg. (CAPE, 2012)

There is an asymmetry of incentives on the government and contractor sides. The government has less incentive to negotiate and keep good deals than the contractor counterparts. Civil servants in some organization receive at best a small annual bonus regardless of outcome, whereas executives at prime contractors can make much larger bonuses if profits are high. In the case of the Department of Defense, program office program managers are often military officers. These officers rotate every few years. They have an incentive to please their current boss by getting a low bid from a contractor, but they have little interest in knowing the true eventual cost because they will be gone in a few years. Program managers and civil servants who negotiate contracts have no *skin in the game*. (Taleb 2018)

There is also an indirect incentive to government program managers to not be too hard on defense contractors. Retired government executives and military leaders retire and then go work for industry, although the reverse never seems to happen. For example, colonels and captains typically retire in their 40s and general officers and admirals in their 50s. They have many working years post-retirement before they fully retire from work. These individuals have extensive knowledge and experience and often go to work for the prime contractors that they used to negotiate with for lower prices.

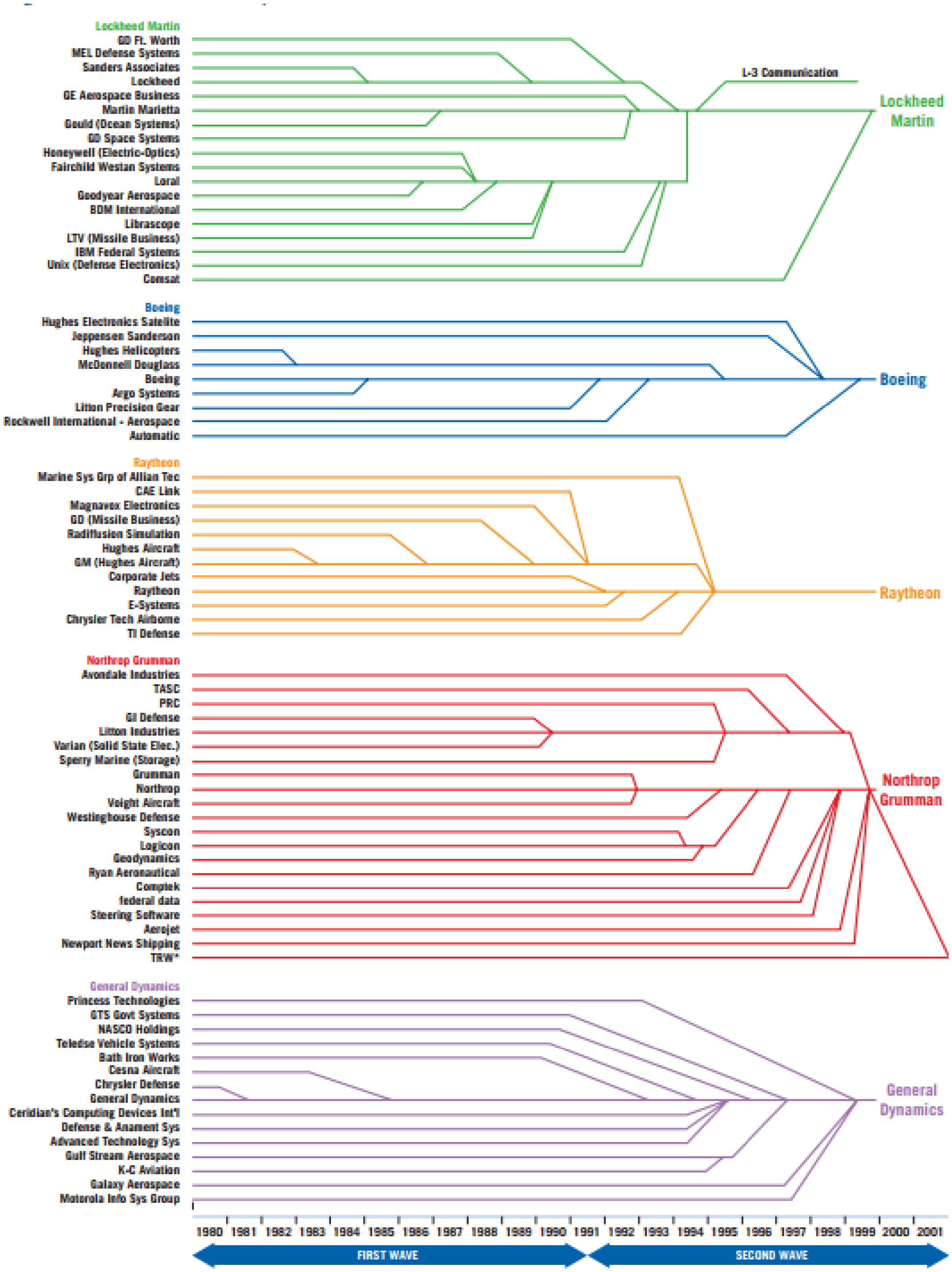
Economic models traditionally have assumed perfect information. The lack of perfect information also leads to asymmetries that make it more difficult for the government to exercise monopsony power.

The Oligopolistic and Monopolistic Nature of Prime Contractors

The defense market also has a limited amount of competition on the prime contractor side. There are a few large sellers. Economists refer to the case in which there are a few sellers as an oligopoly. There are now five large companies that have most of the prime contracts for defense, even though there used to be dozens of such firms.

There has been significant industry consolidation over the last 40 years, resulting in a few large contractors that are left with a great deal of leverage since there is less competition. The amount of consolidation is stunning. Between 1980 and 2000, 77 companies merged into five large giant corporations - the “Big 5” – Boeing, Lockheed Martin, Raytheon, Northrop Grumman, and General Dynamics. (Walker 2002)

See Figure 3. As of 2015, these five companies had $80 billion of defense business and employed 500,000 people. (Choi, 2016)



* Merger Pending Approval

Figure 3. The Great Aerospace Industry Consolidation. (Source: Walker 2002)

Note that in Figure 3, the TRW and Northrop Grumman merger was still pending approval when the report listing the industry consolidations was published. That merger was finalized in late December 2002.

Notice that among the list of companies, there are some that were somewhat extreme products of diversifications. For example, what was Goodyear, a tire company, doing in the Aerospace business? (Fun fact – during the 1970s, the world's largest Goodyear plant in terms of number of employees was in Gadsden, Alabama, the hometown of one of the authors. His father was a Goodyear employee for 35 years). Also, some of the companies were divisions of larger companies that were purchased by another company that was eventually purchased by Lockheed Martin. For example, in 1993, Lockheed acquired the Ft. Worth division of General Dynamics. Regardless, there has been a significant decrease in the number of companies in the defense and aerospace business since 1980.

Secretary of Defense William Perry in the early 1990s encouraged defense industry consolidation because of the anticipated reduction in defense spending after the end of the Cold War. This was part of his initiative to reduce fixed overhead costs in the defense industry. The idea was like the base realignment and closure program which eliminated unneeded facilities. (Flamm 2005) Prime contractors argue that consolidation leads to efficiencies that results in lower prices for the government. The gist of their argument is that fewer firms in a market leads to fewer overhead pools, fewer systems engineers, and fewer program managers at the prime contractors. Unfortunately, the bigger outcome of this consolidation was greater negotiating and political power by the five giants of the defense industry.

The trend of consolidation continues. The $7 billion acquisition of Orbital ATK by Northrop Grumman received approval in 2018. (Northrop Grumman 2018) Orbital ATK has most of the solid rocket motor manufacturing capability in the U.S. and is effectively a monopoly for large solid rocket motors. (Erwin 2018) Orbital ATK itself is the result of a 2015 merger between Orbital and ATK. In 2018, United Technologies acquired Rockwell Collins for $30 billion. (United Technologies 2017, 2018)

In the market for liquid rocket motors, Rocketdyne was a division of Boeing for 9 years until, when Boeing sold it in 2005 to the parent company, United Technologies, of its primary competitor, Pratt & Whitney, to form Pratt & Whitney Rocketdyne. In 2013, United Technologies sold Pratt & Whitney Rocketdyne to the parent company of another of its competitors, Aerojet, to form Aerojet Rocketdyne.

The industry consolidation also permeates outside government customer products. For example, in the commercial aircraft market, Boeing and Airbus effectively now have a duopoly. (Pearlstein 2018)

Another issue limiting competition is data rights. If companies invest any of their own money into the development of the hardware, they own the data rights. Even for developments fully funded by the government, unless the government negotiates up front to purchase these. However, these can be quite expensive. They are expensive enough that the government is not usually willing to pay for them at the beginning of the program. Without the full technical data, the government cannot compete production without redeveloping the product all over again. This is a prohibitively expensive undertaking, since the cost of development programs range in the billions of dollars. The result is a monopoly in production for the prime contractor. We discussed in the section on government monopsony that the fact that there is one buyer leads to cost growth for development programs.

As an aside, for all the ballyhooed direction to compete all contracts, we have never heard anyone advocating the enabling of competition in production by spending the money up front to buy the data rights. It would be even more efficient for the government to pass legislation requiring the delivery of technical data as a part of every government-funded development program.

A recent study of the market power of firms shows that this is a widespread phenomenon. Two European economists found that the average of amount of markup has increased markedly over time, from 18% in 1980 to 67% in 2017. (De Loecker and Eeckhout 2017) Mark up is the ratio of price to marginal cost. The closer this is to 1, the closer prices are to firms' costs. If a firm had little market power, there would be little markup. The increase in markup means higher prices on the goods that the government purchases.

The markup for defense goods has been notorious for decades. As mentioned in the introduction, in 1985, one newspaper headline was "Pentagon pays $640.09 per toilet cover, gives new meaning to 'throne,'" (Deseret News 1985) and just last year the price to the government for a new toilet cover was an outrageous $10,000. (Weisberger 2018) Even adjusted for inflation the $640 toilet seat seems cheap by comparison! In 2011, there were reports of huge markups in the market for Army helicopter spare parts, including a $12.51 gear that is smaller than a dime for which the Department of Defense paid $644.75; and in 2014, the Department of Defense paid $492.17 for a straight-headed pin that cost $36.08. (Grazier 2018)

Even when the five big prime contractors are competing for contracts, there are even fewer companies that can compete for some specific programs. There is more than a passing resemblance between the DoD and the old Soviet Union in terms of its central, and thus its efficiency (or rather lack thereof). In most defense and aerospace commodities (e.g., missiles, satellites), there are only two or three prime contractors. (Lofgren 2017, 2018) For example, in 2018 Lockheed Martin had largely been shut out of the target missiles market due to inability to compete on price. And if it had not been for a large radar contract development contact win in the last few years, they would have been shut out of the large, ground-based radar market. There was even some discussion at one point among some senior leaders to provide Lockheed Martin with some money for radar studies to enable them to compete in that market!

Also, changes for these large contractors are like trying to turn a large ship. It takes time to make changes. In the authors' experience, any sufficiently large organization is a bureaucracy. The creation of giant corporations through these mergers leads to a level of inefficiency that approach that of the internal workings of the government.

The power of these large primes relative to the government has led to the maxim that, when the government works with prime contractors, it is a case of "If heads, the government loses. If tails, the contractor wins," meaning that the large prime contractors will make money regardless of a program's cost or schedule performance. Senior leaders in the Department of Defense have admitted in the presence of one of the authors (Smart) that the defense industry takes no financial risk. If something goes wrong, the government, and hence the taxpayer, pays the bill, even when the contractor is at fault.

There is a great deal of pressure from within the Department of Defense to compete contracts as much as possible, but that competition would be more effective if there were more companies to bid on these contracts. The oligopoly in the defense contractor market enables and incentivizes collusion to keep prices higher, either explicitly or tacitly.

Collusion – Explicit and Tacit

If the sellers recognize their interdependence, the result can be monopoly pricing with the few competitors sharing the monopoly profits. (Chacholiades 1986) It is well known that there are few sellers, so surely Lockheed Martin, Boeing, Northrop Grumman, General Dynamics, and Raytheon recognize their interdependence. Indeed, these contractors do not just compete with one another, they are often subcontractors to each other on large efforts. For example, on the Army's Patriot terminal missile defense program, Lockheed Martin is the prime, while Boeing develops a major component, the seeker, and thus is a subcontractor to someone who is also a competitor on other prime contracts.

This sets up the potential for collusion. "Collusion is an agreement, usually illegal and therefore secretive, which occurs between two or more persons to limit open competition by deceiving, misleading, or defrauding others of their legal rights, or to obtain an objective forbidden by law typically by defrauding or gaining an unfair advantage." (Brandly 2010) Indeed, the notion that oligopolists collude started with Adam Smith – "people of the same trade seldom meet together…but the conversation ends in… some contrivance to raise prices." (Kreps 1990) Profits would be maximized if there were a single firm, which is the case of monopoly. As interactions between oligopolists are repeated a monopoly equilibrium in which the oligopolists share the monopoly profits can be sustained. Indeed, oligopolistic firms will collude as much as possible, in accordance with the profit maximizing motive. (Kreps 1990) An example of an overt collusion is the Organization of Petroleum Exporting Countries cartel, a consortium of 15 countries, most of which are in the Middle East. These countries often attempt to coordinate reductions in oil production to keep prices higher, and thus their profits higher.

In the United States such explicit collusion among firms is illegal. However, there are reported instances in which oligopolists explicitly collude with one another, sometimes using extremely clever means. As an example, in the 1950s, four firms comprised the market for heavy electrical equipment. General Electric (GE) had 45% of the market, followed by Westinghouse at 35%, with Allis Chalmers and Federal Pacific each with 10%. The heads of these companies would meet at golf courses and restaurants to establish the winning and losing bids. The winning bids were rotated based on the phases of the moon. The Tennessee Valley Authority uncovered this collusion when they realized that they had received the same bids over a three-year span. (Cabral 2000) Once the collusion was discovered, the companies involved along with four executives from these firms were indicted for price-fixing. From 1960 until 1962, prices in this market dropped by 50%. Allis-Chalmers left the heavy electrical equipment market altogether. In 1963, however, GE published a pricing book, which contained the information needed to determine what GE would bid. GE also announced it would follow its published guidelines without any deviation. GE even hired an accounting firm to make sure that the company followed the rules established in the pricing book. Westinghouse followed GE by publishing its own pricing book. Except for a brief period in 1964, the prices that both companies charged for its products remained stable and identical until 1975, when the Department of Justice determined that GE's and Westinghouse's practices violated antitrust laws. This ended the tacit collusion between these two companies. (Cabral 2000)

Collusion is notorious in auctions. One of the ways in which bidders can collude with one another is by coding information into bids. Governments began auctioning the radio, television, and phone spectra in the 1990s. To encourage competition, bidders typically cannot explicitly communicate with each other, but there have been instances in which they have encoded messages in their bids. For example, a bid equal to $100,401" could mean "I intend to bid on license 401, don't compete with me." In repeated bids, bidders can use other means such as punishing rivals if they do not implicitly collude. (Klemperer 2001)

The argument has been made that, in the absence of collusion, competition between two or more competitors should result in prices that are as low as they are in perfect competition. The incentive is there for each company to undercut the other, and it is rational to believe that the winning bidder will set the price equal to the marginal cost. To study this phenomenon, we turn to game theory. Game theory is not the study of chess or checkers or poker, but rather models of conflict and cooperation among decision makers. For example, consider one of the canonical examples of game theory, called the Prisoner's Dilemma. It is so named because it involves two prisoners, each of whom can either stay silent or fink on one another to get a lesser sentence. A prisoner can only get a lesser sentence if he or she is the only one to confess. If both confess, they both get longer sentences than if they had both stayed silent. We adapt the Prisoner's Dilemma slightly for acquisition. Suppose that there are two contractors bidding on a single contract. Also, suppose that each contractor can either submit a high bid equal to $6, or a low bid equal to $4. If both contractors submit the same bid, the government will randomly award the work to one of the two contractors by means of a coin flip. If one of the contractors submits a low bid, and the other a high bid, the government will award the work to the low bidder. If company A submits a high bid, and company B a low bid, then company A gets $0, and company B gets $4, which we represent by the ordered paid (0,4). If both companies submit high bids, the contract is awarded for $6 to one of the companies at random, so the expected value of the award for each company is $3, which we represent as (3,3). If both companies submit a low bid, the award is $4, so the expected value of the award to each company is $2, which we represent as (2,2). The actions and the outcomes of this game can be represented by Table 1.

		Company B	
		Bid High	**Bid Low**
Company A	**Bid High**	**(3,3)**	**(0,4)**
	Bid Low	**(4,0)**	**(2,2)**

Table 1. Payoff Matrix for the Prisoner's Dilemma.

One of the key assumptions is that the setup is non-cooperative, in that Company A and Company B make their choices without knowing what choice the other company is going to make, although the two choices and the two outcomes are known to both companies. If Company A submits a high bid, its expected return is $3 if Company B bids high. In that case, Company B also expects to receive $3. If Company B bids high and Company A bids low, it wins the work with certainty, and B gets nothing. Thus, if Company B bids high, Company A expects to receive $3 if it bids high, but $4 if it bids low. Thus, if it were to know that Company B would bid high, then Company A should bid low. On the other hand, if Company B bids low, and Company A bid high, Company A will lose the work with certainty and receive nothing. If Company A bids low, then it has a 50% chance of getting the work and expects to receive $2. Thus, if it knew Company B would bid low, then Company A should also bid low.

In both cases, regardless of whether Company B bids high or low, Company A's best choice is to bid low. This game is symmetric, so Company B's best choice is to bid low as well. For this pair of options, call it Low, Low, neither company has an incentive to change its choice given the choice of the other company. If both bid low, changing to a high bid will only cause that company to lose the work with certainty.

Unless one of the companies is naive, both will compete, leading to a competitive outcome. In this case, the choice of low bids for both contractors is called a Nash equilibrium, after John Nash, who developed the concept and was awarded a Nobel Memorial Prize in Economics in 1994 for the concept.

Thus, if competition were a one-time event, only two firms are needed to provide a fully competitive market. However, in real life, there are multiple interactions that occur over an extended period. To be consistent with the nomenclature of the academic literature on game theory, we call a high bid “cooperate” and a low bid “defect.”

In the case of a few firms competing for contracts, the interactions take places numerous times over a period of decades. To model this concept, we can still use the Prisoner’s Dilemma, but in a repeated form known as the Iterated Prisoner’s Dilemma. Now in terms of strategy, each player not only has to consider which action to take in the current competition, the player also must decide how to respond to the opponent’s action from the previous competition. If the opponent cooperated last time, does that mean a player should cooperate this time, or defect? One strategy would be to always cooperate, regardless of the opponent’s actions. This is not optimal since if the opponent through trial and error discovers that a player will always cooperate, the opponent will eventually learn to always defect. On the other hand, a player that always defects will invite defection. The first situation leads to a situation in which one player is always taken advantage of, while the second leads to the single-stage equilibrium, just repeated many times. One alternative solution would be to begin the game by cooperating in the first round and continue to cooperate if the opponent cooperates. However, should the opponent ever defect, the player will defect from that point forward. This strategy is called Grim Trigger. An alternative, more forgiving strategy would be to begin by cooperating; then cooperate if the opponent cooperated on the last round; and defect if the opponent defected on the previous round. Like Grim Trigger, this strategy starts by cooperating, but unlike Grim Trigger, the player will begin cooperating again if the opponent changes back and cooperates in the previous round. This strategy is aptly named Tit for Tat. This strategy has a cooperative, forgiving aspect, of being willing to cooperate if the opponent will. However, unlike the always cooperate strategy, Tit for Tat punishes an opponent that tries to take advantage of its cooperation. (Axelrod 1984)

There is no theoretical consensus on a best strategy. If the game were repeated a finite, and known number of times, the equilibrium strategy, by backward induction, would be to defect on every round, since the best strategy on the last round is to defect. In the case of an infinite number of rounds, there are multiple equilibria, some of which involve cooperation. However, in the real world, there is not an infinite horizon, but neither is there a fixed number of rounds that is known to both players.

To determine how such strategies might play out in the real world, the political scientist Robert Axelrod conducted a computer tournament of the Iterated Prisoner’s Dilemma in 1980. Axelrod solicited submissions of computer programs from game theorists for playing the Iterated Prisoner’s Dilemma. The tournament format was round robin. Each program played against the other programs and against a random program that randomly cooperated or defected on each round with 50% probability. Each game consisted of exactly 200 rounds.

The total score for one game was the sum of the payouts generated over each of the 200 rounds of play between two opponents. The total score for the tournament was the sum of the payouts for each game summed over all games played by an individual program. Fourteen programs were submitted by a variety of academics, including prominent professors in the fields of economics, mathematics, psychology, political science, and sociology. The winning submission was Tit for Tat, which was a simple, four-line program written in BASIC. It was much simpler than the last place submission, which consisted of 77 lines of code. The programs included a variety that tended toward cooperation versus those that tended to defect. Each of the top eight finishers tended toward cooperation in the sense that none of them defected first. None of the other entries had this property. One interesting feature of Tit for Tat is that it was the most forgiving program that was submitted, in terms or returning to cooperation after a defection. (Axelrod 1984)

The results of the first tournament were published. Axelrod repeated the tournament a year later to see if anyone could improve upon the Tit for Tat strategy. He opened the second tournament by advertising for submissions in journals for computer users (called “small computers” in the early 1980s). This time, there were 63 entries from six countries. Tit for Tat was submitted again, and again was the simplest program. The other programs submitted fell into two largely groups. One group decided that the forgiving nature of Tit for Tat was to be emulated and submitted strategies like Tit for Tat. One program submitted, Tit for Two Tats, was even more forgiving than Tit for Tat, in that it would endure two defections in a row before it began to retaliate by defecting as well. The other group seemed to think that because Tit for Tat was the winner of the first tournament that many people would submit forgiving strategies like Tit for Tat, so they designed programs designed to take advantage of this possibility and their programs were designed to find clever ways to defect. Despite this, Tit for Tat also won the second tournament. No one was able to improve upon the results of Tit for Tat, even knowing that Tit for Tat won the first tournament. The rules allowed for anyone to submit any program, even those that were submitted for the first tournament. Only one person submitted Tit for Tat for the second tournament, who was the individual who submitted the same program for the first tournament. Once again, the programs that never defected first did better than the others – they comprised the top seven finishers, and 14 of the top 15. (Axelrod 1984)

Axelrod also conducted a simulated tournament to simulate a survival of the fittest process for the programs. Each of the programs from the second tournament were run against one another in a sequence of tournaments. Each started with the same number of instances, but on each subsequent round, their proportion change based on their success in the previous round. The result is that the more successful programs came to represent a larger proportion of the total number of programs in the population, while the less successful programs came to represent a smaller proportion of the total population. There were 1,000 rounds conducted for the tournament, at which point the populations stabilized. Axelrod conducted six of these sequential tournaments. Tit for Tat was the winner of five in terms of comprising the largest proportion of the number of programs relative to the others. The less successful, less cooperative rules did not do well in the survival of the fittest tournaments. There was only one non-forgiving strategy to survive beyond round 200. (Axelrod 1984)

Even in cases where cooperation is least expected, it often emerges even between enemies. A notable example is trench warfare during World War I. Trench warfare can be thought of as a Prisoner's Dilemma problem. At any given time, the choices are to not shoot (cooperate) or to shoot (defect). The Western Front, a 500-mile line in France and Belgium that was the main theater of battle for much of the conflict, was the scene of multiple horrific battles that resulted in cumulative casualties that counted in the millions. However, in between the monumental encounters, a live-and-let-live system developed in the trenches on both sides of the Western Front. A famous instance is the unofficial Christmas truce in 1914. On Christmas Eve of that year, the soldiers in the opposing trenches lobbied Christmas carols at one another instead of grenades. On Christmas morning, the soldiers agreed to an unofficial truce, exchanging gifts of hats and food. It also allowed the two sides to bury their dead comrades, whose corpses had lain for weeks in the no-man's land between the trenches. (Weintraub 2001)

Even in the absence of overt collusion, tacit collusion could be a learned behavior among companies that have limited competition. In machine learning, there are three classes of learning algorithms – unsupervised, supervised, and reinforcement. An example of an unsupervised learning is clustering. Regression is a commonly encountered example of supervised learning. In regression analysis, the equation is told which data points to fit, and how to fit them. In reinforcement learning, the algorithm must discover which actions yield the biggest reward to trial and error. The reward may be delayed. This is how people learn complex tasks in real life. (Sutton and Barto 1998)

For example, Miles Smart, at the time of the writing of this paper, is one year old. Over the last few months, he has learned, by a process of trial and error, how to roll over from his back to his front, to crawl, pull himself up to a standing position, and started to walk if he can hold onto a structure to aid with his balance. See Figure 4.

Figure 4. Reinforcement Learning in Action with Miles Smart.

Miles used a process of reinforcement, by trying things that worked and did not work, receiving positive feedback for the things that did work, and negative feedback for things that did not, such as a bump on the forehead. From this process, Miles learned to repeat things that work to gradually learn the process of walking.

In the same way, we propose that in the case of limited competition, prime contractors will learn to bid in a cooperative manner above the pure competition price. When there are only two or three prime contractors in any commodity class, there will occasionally be some high bids that win a contract. The contractor will be rewarded in such cases, by staying in business and achieving a higher price. Prices higher than the competitive solution can thus evolve over a period. This tacit collusion would collapse if there were enough firms, but it is easier to maintain when the number of firms is few and they are similar. (Cabral 2000)

This interdependence provides incentives to tacitly collude, in the sense that firms are less likely to engage in price wars. For example, there are two corporations, Anheuser-Busch and MillerCoors, that control 90% of the beer market in the U.S. Back in the 1980s, when Miller and Coors used to be two separate companies, there was an interesting display of Tit for Tat. In 1988, both Miller and Coors cut prices on their main beers, resulting in an even greater price reduction by Anheuser-Busch. Miller and Coors soon raised their prices back to where they were, and Anheuser-Busch followed suit. (Tepper 2019)

Another way to explain potential apparent collusion in the aerospace and defense industry is fluctuating government demand. The large prime contractors have a large infrastructure that enables them to work on multiple programs simultaneously. A price war or defection from the norm for the large prime contractors would be to cut their fixed costs, especially overhead, severely, creating a lean organization. However, when there is a large amount of work, and no one project is large enough to comprise a significant percentage of the total work, it can be difficult for companies to project how much infrastructure they need. Also, there are significant fluctuations in defense budgets over time, and projects take years to complete.

If demand is underestimated, a company could miss out on work, or, having won new work, struggle to ramp up by hiring additional personnel and potentially enchancing additional infrastructure. On the other, if they overestimate the amount of work they will win, they may not be competitive. For development, cooperation or tacit collusion takes the form of a large infrastructure, or fixed cost. Rather than an attempt to collude, the uncertainty in demand can explain the higher infrastructure. To see this, we turn again to game theory.

In addition to the matrix form of a game that we presented earlier for the Prisoner's Dilemma, games can also be expressed in extensive form, which takes the form of a tree. For example, consider a game in which the contractor and the government must agree on quantity produced per year. Suppose that the contractor believes that the government is equally likely to want 20, 30, or 40 units per year. If the contractor sets up its infrastructure for 20 per year, it will only sell 20 per year regardless of demand. By setting up its infrastructure to build 40 per year, it will have higher expected revenue and can do no worse than if the government only purchases 20 per year. Given that the government will have to pay for the fixed cost associated with this infrastructure, the contractor has nothing to lose by setting up its infrastructure to produce the maximum possible. The government pays more by having this uncertainty. See Figure 5.

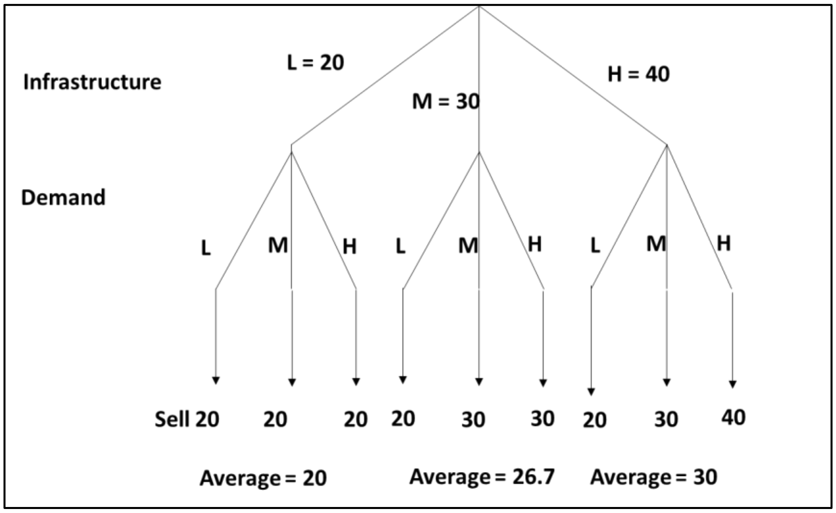


Figure 5. Extensive Form of Infrastructure Demand Game.

Prime contractors will plan for a larger infrastructure, and incur higher fixed costs, to avoid missing out on potential profits when demand is high. Thus, even when there are a few sellers, for development, uncertainty in demand causes higher fixed costs, leading to an apparent tacit collusion by prime contractors that results in higher cost and prices for the government customer and ultimately the taxpayer. Therefore, for a variety of reasons, there is little effective competition in development, and almost no competition in production and operations.

Monopoly

The problem with a monopoly defense contractor is that the government receives less output for a higher price than under a pure competition situation. In the case of pure competition, the firm is a price taker, while under monopoly it is a price setter. Under pure competition, the firm makes zero profits (accounting for opportunity costs), and the marginal cost is the supply curve and is equal to the average revenue, which is the demand curve. Under monopoly, the single firm maximizes its profits by setting the price where marginal revenue equals marginal cost. Marginal revenue is always less than average revenue, which results in a higher price and a lower quantity produced. This excess is provided to the monopolist. See Figure 6 for an illustration.

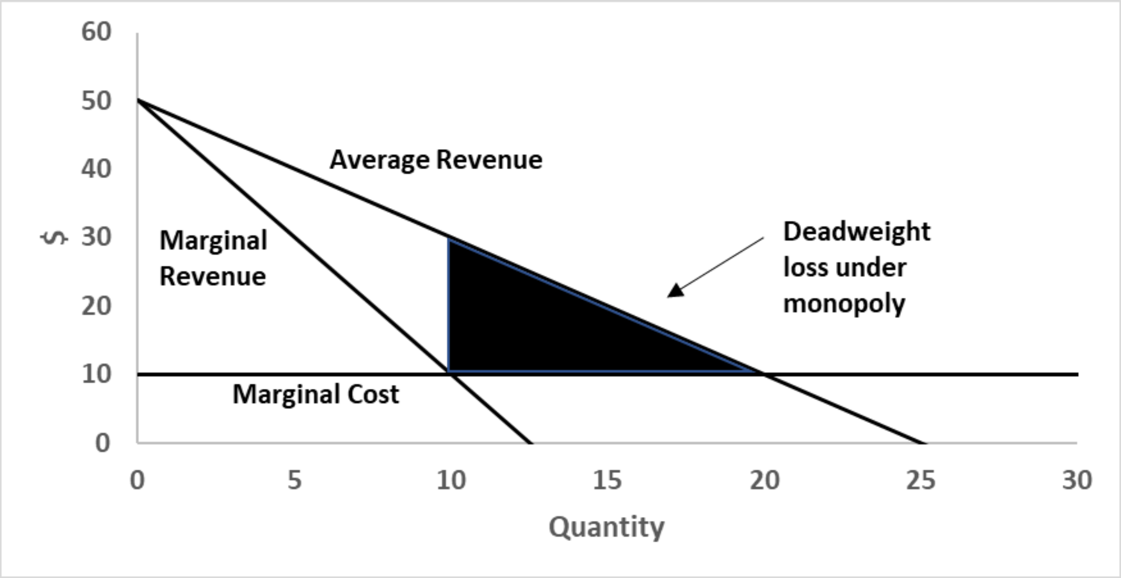


Figure 6. Illustrating Deadweight Loss Under Monopoly.

In the case of pure competition, the price would be equal to the marginal cost, and the quantity consumed would be where the marginal cost curve intersects the demand curve, i.e. the average revenue curve. For the example in Figure 5, this would be a price equal to $10 and a quantity equal to 20.

In the monopoly case, the producer sets the price so that it accords with the quantity at which the marginal revenue equals the marginal cost, which is at a cost equal to $10, a quantity equal to 10, and a price equal to $30 that is significantly higher than cost. The deadweight loss in this case is the area of the shaded triangle, which is ½*$20*10 = $100.

This is the classical economics view. But as pointed out by economists the deadweight loss underestimates the true cost of monopoly profits. (Tullock 1967) There is also the cost that the monopolist incurs to keep his monopoly. In the case of government contractors, this would be partially accounted for by lobbyists in Washington, D.C. The large defense contractors have money to spend on lobbyists to protect their interests. On the government side, there is the cost of antitrust, which is currently very minimal and has been since the early 1980s. (Tepper 2019)

The profits achieved by monopolists are above and beyond what should be achieved in a competitive market by innovators. These profits are akin to a type of rent that is extracted from taxpayers. It is a detriment to our national security, since it results in lower quantities. What can be done? In the long run, two options are to apply antitrust regulation and break up the large prime contractors into smaller companies. Another possible long-term solution is the market solution. That is, the commercial companies that are currently providing lower-price access to space could also supplant the traditional large defense contractors or force them to be more efficient in order to survive. These companies include Space X and Blue Origins, among others. Another factor leading to higher prices is that government organizations often optimize for performance, neglecting the cost- and schedule-tradeoffs implicit in this arrangement. The commercial companies optimize for cost. The prime traditional organization for launch vehicles is the United Launch Alliance (ULA), a consortium of Lockheed and Boeing. The average ULA cost per launch is $422 million, while SpaceX's is much lower, between $83 and $96.5 million for two recent contracts. (Wang 2018) That is 77-80% less. Could a commercial wave also reduce costs for weapon systems and satellites? The potential is there, but there is a great deal of resistance. The commercial paradigm challenges the belief systems of the very bureaucrats that determine the contractors who provide the services. Over a decade ago, Space X's Vice President for Operations stated "NASA optimizes for performance. We optimize for cost. [NASA] pays five time the cost for the last 5% of performance." (Hoffman 2007) Even more controversially, one of the authors heard a three-star flag officer describe a conversation with Elon Musk about cutting costs. Reportedly, Elon Musk told the officer "systems engineering is for dummies. I don't need it." This type of talk discouraged the officer from pursuing commercial options, even though cutting back on program management and systems engineering is one way that the government could save costs. The government is interested in reducing cost, but, when doing so threatens the existing bureaucracy, there is hesitation. A defense agency with an annual budget equal to $10 billion that employs 1,000 systems engineers as civil servants means that there is an embedded bureaucracy that will resist the urge to cut cost by significantly reducing systems engineering. These government systems are often over-engineered, with the prime contractor developing the program once, and the government re-doing much of their analysis. Rather than providing just a check, the government typically goes above that and re-does much of the engineering analysis. However, as the Seinfeld character Cosmo Kramer said when someone touted a low-carb diet, "But what kind of pizza can I have on the diet?" The person explained that pizza had way too much bread to be part of a low-carb diet. After asking a few more question, Kramer again asked "But what kind of pizza can I have on the diet?" The requirements of a low-carb diet were not palatable to Kramer. Kramer would like to lose 10 pounds but is not willing to make the changes required to achieve his goal. In the same way, the government would like to save money but when told what is required to achieve savings, is not willing to make the changes required. In the long-term then, encouraging competition is a key to achieving savings. However, this requires more companies competing in this market. This could be achieved by either breaking up existing large companies into smaller ones or enabling paradigm-busting commercial companies like SpaceX to compete in this market.

Another option would be to pass legislation so that the government receives technical data packages, i.e. the "blueprints," for all development programs that it fully funds will enable competition in production. However, this faces the opposition of the five large defense companies lobbyists on K Street in Washington, D.C.

All these solutions will take time. In the short-term, the government is at a strategic disadvantage, like the military warlord Kong Ming in the story that kicks off the introduction of this paper. To deal with this disadvantage, we can make use of strategy to engineer the acquisition process to the government's advantage.

Market Intervention and Mechanism Design

Game theory can be used to achieve better value in purchasing production units in a monopoly competition environment. The way to do this is turn flip game theory on its head. Mechanism design involves designing a game, or market, that achieves a desired outcome. It is a way of engineering the acquisition process to achieve desired ends. It is also referred to as "reverse game theory." (Hurwicz and Reiter 2006) It has been successfully used to auction the radio spectrum and oil drilling rights. The founders of mechanism design were awarded the Nobel Prize in Economics in 2007. A similar field of study is market design which has been successfully used to match kidney donors and recipients. The founders of market design were awarded the Nobel Prize in Economics in 2012. (Roth 2015) The government already deals with this to some extent. An example of such a mechanism is the multi-year contract, in which the government gives up the ability to manipulate quantities purchased every year in exchange for lower prices.

In keeping with the context of this paper, the focus will be obtaining better value from a defense contractor that is effectively a monopolist in production. In what follows the marginal revenue curve is ignored, since the government as regulator and customer, will not have insight into the firm's marginal revenue. We assume that the demand curve is known to both the firm and the regulator. We will also assume that the government does not know the firm's exact costs. In this discussion, the government is referred to as the principal, and the contractor as the agent.

This kind of market intervention is in keeping with free market principles. Friedrich Hayek wrote in *The Road to Serfdom* in 1944, "There is, in particular, all the difference between deliberately creating a system within which competition will work beneficially as possible and passively accepting institutions as they are." (Hayek 1944)

Incentives in contracts have been showed to work in practice for government programs. A recent example is a road construction project in Huntsville, Alabama that was originally planned for four years. By using incentives for finishing early, as well as penalties for finishing late, the project was completed 11 months early. (Olson 2018)

Even though there are data reporting requirements written into the law for Department of Defense programs, the firm's costs are not always known by the government. The Department of Defense has historically required reporting of costs for Major Defense Acquisition Programs for many years. In 2017, new legislation lowered the threshold for cost reporting for all programs costing at least $100 million. At least one of the independent agencies, the Missile Defense Agency, has even more stringent thresholds for cost reports. NASA collects cost and technical data, although there are no legislative requirements. Some large NASA programs have never had useful cost reports. This includes the International Space Station and the Space Launch System. Also, in one of the author's experience, there are many challenges to obtaining useful cost reports. There is no positive incentive for the contractor to provide high-quality cost data, as it provides the government with leverage for negotiating contracts. If the government knew the contractor's cost, it could make a take-it-or-leave-it offer to cover the contractor's fixed and variable costs, leaving it with no profit. Even if the government had to offer some profit to get it to deliver the product, it could greatly reduce the contractor's profits. In fact, the contractor has a negative incentive to not reveal its costs to the government.

The government program manager has no interest in the cost reports, as it does not benefit his current project, although it will be useful to the program manager's successors (note that by cost reports for DoD we are referring to the cost and software data reports, not earned value data). There can be some negative incentive if cost reporting requirements are an award fee criterion, but, in one of the author's experience, it is rare for a contractor to be penalized in award fee for not providing high quality cost reports. Even when the cost reports provided are technically correct, they can still be misleading.

One program that one of the authors worked on reported the bulk of the cost in the correct account, but the overages were reported in a separate account. It took a deep dive into the contractor's cost to discover this discrepancy. This occurred after several years during which the government perception was that the costs were lower than actual.

For another program, the initial cost reports were removed from the contract after the contractor told the program manager that the program would save millions of dollars if the requirement was removed. After reports were later added back to the program, the contractor could not provide accurate values for the unit costs of the system. It was only after a year-long effort to dig deep into the prime contractor's and major subcontractors' data and multiple face-to-face meetings that the government program office had accurate details on the unit cost of the system.

The government needs detailed insight into the fixed and variable costs for a program in to know the true production costs, particularly how production costs change as a function of the total quantities and the rate at which they are produced. The authors are aware of only one ongoing program, the Missile Defense Agency's Terminal High Altitude Area Defense, that is actively collecting fixed and variable costs from the prime contractor and its major subcontractors. (Crowe and Embrey 2016)

Thus, we see that even in the case of cost reporting requirements, the government may have some uncertainty about the fixed and variable cost of a system.

If the government knew the contractor's costs, it could simply tax some portion of its profits. However, this is inefficient in the sense that the government pays the contractor, then gets some of its own payment back in the form of taxes. A better way to handle the issue is for the government to employ a mechanism for achieving its ends up front.

Knowing the costs are important. As mentioned earlier, if the government could design a mechanism that would force the contractor to reveal its costs, it could achieve a better deal, either getting a better price or getting a greater quantity.

It turns out that we can focus our attention on mechanisms that only require the contractor to report its true costs. This is the Revelation Principle, which states that any mechanism is equivalent to an incentive-compatible mechanism by which agents reveal their private information to the principal, or planner. (Laffont and Martimort, 2002)

In this case, the private information is the firm's cost. We will describe two mechanisms to achieve a better result than letting the monopolist firm set its own price. To help motivate the analysis and keep it simple, we will graphically analyze the results with demand curves. We will also ignore fixed costs. We assume that these are covered and paid for by the government and look only at the marginal costs of production. If the fixed cost is not a function of quantity, the results will not be affected.

To motivate the discussion, consider the graph in Figure 7.

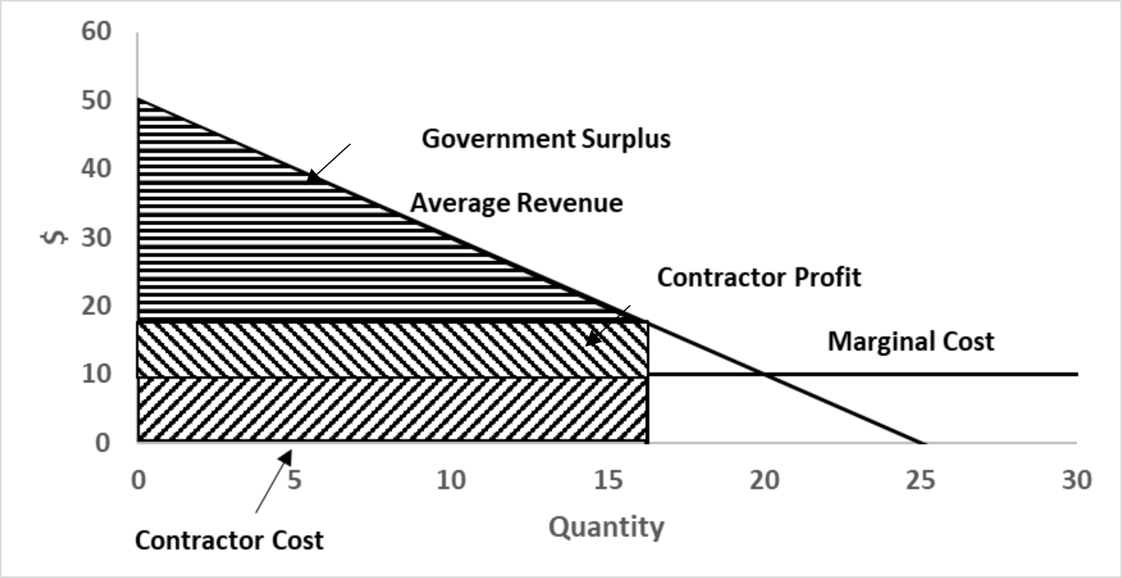


Figure 7. Contractor Profit, Cost, and Government Surplus.

In Figure 7, the contractor cost is the area below the marginal cost line, up to the quantity produced. The contractor profit is the area above the marginal cost line and the price charge to the government. The government's surplus is the area above the profit. The total value to the government is the total area under the demand curve up to the quantity. Thus, the surplus is the difference of the value it derives as provided by the demand curve minus what it pays to the contractor.

One mechanism for achieving higher output would be to pay the contractor its reported cost plus all the government surplus. See Figure 8. (Loeb and Magat 1979)

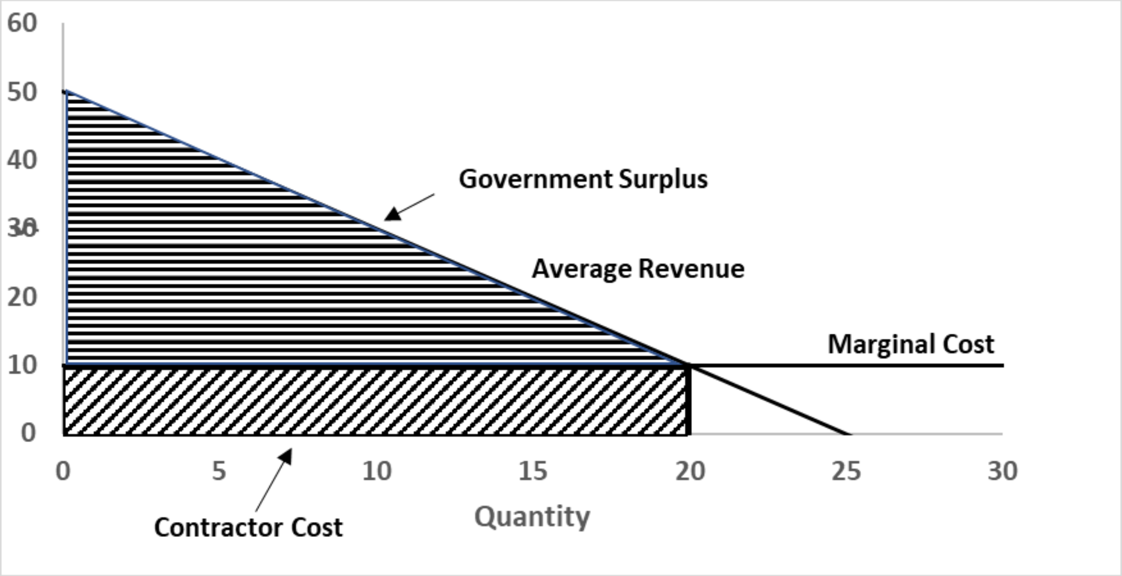


Figure 8. Achieving Higher Output by Sacrificing Surplus.

In this case, the contractor would report its cost. The government would then buy the quantity on the demand curve that intersects the contractor's marginal cost curve. The government would buy 20 units at $10 each.

Note that the contractor will maximize its profits under this agreement only by reporting its true costs. If it were to report a higher cost, the government would buy less, and thus the contractor would leave money on the table. For example, if the contractor said its cost is $20 for each unit, the government would reduce the quantity it purchases to 15 units, and the contractor would miss out on the profits it would receive for units 16-20. Since it receives all money under the demand curve, the contractor does not gain by selling for a higher price.

If the contractor underreported its cost, the government would buy more than 20 units at a value less than the contractor's cost. Up to a quantity of 20 there is a surplus, so the contractor would cover its cost. For quantities greater than 20, there is no surplus, so the contractor would lose money on every unit above 20 units.

Note this is the competitive market solution. However, this comes at a cost – the government provides the contractor its entire surplus. The contractor's profits are the entire area under the demand curve that is greater than the cost. The surplus is now the contractor's profit. We could integrate or just note that the profit is a triangle, so the profit is $40*20/2 = $400. Note that the contractor profit under the standard monopoly situation without the mechanism, as in Figure 7, is $200. The average unit cost to the government in the standard monopoly situation is $30. Under the mechanism, the average unit price is ($400+$200)/20 = $30. This only accounts for the marginal costs. Once the fixed costs are added in, this mechanism will result in a lower average unit price for the government. By implementing the mechanism, the government can buy greater quantities at a lower price. Procuring greater quantities for the same unit price is a significant benefit if this is a weapon system that is critical for the defense of the nation. The Loeb-Magat mechanism thus results in increased output with little change in the cost to the government. It basically trades the deadweight loss for the government's surplus (aka the consumer surplus).

We now consider a different mechanism, one that will result in less quantity produced but at less cost to the government. (Baron and Myerson 1982) We assume that the government knows the fixed cost but has uncertainty about the marginal cost. We assume that the contractor knows the marginal cost (seems like this should always be the case, but after looking at contractor cost reports for many years, the authors have serious doubts). We assume that the government has some idea about the marginal cost and can bound the cost and form a distribution on the cost. Let f denote the probability density function for this cost, let θ denote the true marginal cost, and let θ_0 and θ_1 denote the lower and upper bounds for the cost, respectively.

We assume that both the government and the contractor know the demand function. Let P denote the demand function, that is $P(q)$ is the price at which quantity q is demanded.

The total value *V(q)* to consumers of an output quantity q is the area under the demand curve, viz.,

$$V(q) = \int_0^q P(\tilde{q})d\tilde{q}.$$

The surplus for the government (aka consumer) is thus *V(q)-qP(q)*. By the Revelation Principle, only consider those policies under which the contractor reveals its true marginal cost per unit θ need to be considered. The policy prescribed by the Baron-Myerson mechanism also applies a subsidy s, which can be a payment to the contractor when it is positive and a tax on the contractor when it is negative. If the contractor reports its cost truthfully as θ, then its profit will be

$$\pi(\theta) = p(\theta)q(\theta) - \theta q(\theta) - k + s(\theta).$$

Let $\hat{\theta}$ denote the contractor's reported cost under the mechanism. Then, $p(\hat{\theta})$ is the regulated price, and the government purchases $q(\hat{\theta})$ per the demand function $p(\hat{\theta}) = P(q(\hat{\theta}))$. Let k denote the contractor's fixed cost, which does not depend on quantity.

If the reported cost $\hat{\theta}$ differs from θ, the contractor's profit is

$$\pi^*(\hat{\theta}, \theta) = p(\hat{\theta})q(\hat{\theta}) - \theta q(\hat{\theta}) - k + s(\hat{\theta}).$$

To guarantee that the contractor has no incentive to not truthfully reports its cost, we must have

(1) $\pi(\theta) = \max_{\hat{\theta}} \pi^*(\hat{\theta}, \theta)$ for all $\theta \in [\theta_0, \theta_1]$.

As mentioned before, the contractor is not willing to lose money, so we must also have

(2) $\pi(\theta) \geq 0$ for all $\theta \in [\theta_0, \theta_1]$.

Also, the price and quantity must be on the government's demand curve, i.e.

(3) $p(\theta) = P(q(\theta))$.

If the policy satisfies (1), (2), and (3), it is feasible, that is, it meets the government's requirements and the contractor has no incentive to misrepresent its marginal cost.

Condition (1) is not useful to derive an optimal policy. To get to an optimal policy, we next derive three conditions that are equivalent to (1) and (2). The first of these is

(4) $q(\theta) \geq q(\hat{\theta})$ for all $\hat{\theta} \geq \theta$.

To see that this holds, note that from the profits equations and (1), that

(5) $\pi(\theta) \geq \pi^*(\hat{\theta}, \theta) = \pi(\hat{\theta}) + q(\hat{\theta})(\hat{\theta} - \theta)$.

That is,

$$\pi(\theta) - \pi(\hat{\theta}) \geq q(\hat{\theta})(\hat{\theta} - \theta).$$

Reversing the roles of $\hat{\theta}$ and θ in the π^*, we see that

$$\pi(\hat{\theta}) \geq \pi^*(\theta, \hat{\theta}) = \pi(\theta) + q(\theta)(\theta - \hat{\theta}).$$

This yields

$$(6) \qquad q(\hat{\theta})(\hat{\theta} - \theta) \leq \pi(\theta) - \pi(\hat{\theta}) \leq q(\theta)(\hat{\theta} - \theta).$$

By transitivity,

$$q(\hat{\theta})(\hat{\theta} - \theta) \ \leq \ q(\theta)(\hat{\theta} - \theta),$$

which means that (4) holds. Since q is a nonincreasing function of θ, it must be continuous almost everywhere in $[\theta_0, \theta_1]$. Also note that, from our proof that (4) holds, it is the case from (6) that

$$q(\hat{\theta}) \leq \frac{\pi(\theta) - \pi(\hat{\theta})}{(\hat{\theta} - \theta)} = -\frac{\pi(\theta) - \pi(\hat{\theta})}{(\theta - \hat{\theta})} \leq q(\theta).$$

Taking the limit as $\hat{\theta} \to \theta$, we find $\pi'(\theta) = -q(\theta)$ for almost all θ. Integrating this equation from θ to θ_1, we find

$$\int_{\theta}^{\theta_1} \pi'(\tilde{\theta}) d\tilde{\theta} = -\int_{\theta}^{\theta_1} q(\tilde{\theta}) d\tilde{\theta}\ .$$

Integrating the left side and rearranging yields

$$(7) \qquad \pi(\theta) = \pi(\theta_1) + \int_{\theta}^{\theta_1} q(\tilde{\theta}) d\tilde{\theta}\ .$$

Thus conditions (1) and (2) imply conditions (4) and (7).

Condition (2) implies that

$$(8) \qquad \pi(\theta_1) \geq 0$$

We claim that feasibility as defined by conditions (1)-(3) is equivalent in the sense that (1)-(3) is true if and only if (3), (4), (7), and (8) are true. We have shown that (1)-(3) imply (3), (4), (7), and (8). To show the converse, conditions (7) and (8) imply (2). To see that (1) holds, from condition (7) we have that

$$\pi^*(\hat{\theta}, \theta) = \pi(\hat{\theta}) + q(\hat{\theta})(\hat{\theta} - \theta) = \pi(\theta) - \int_{\theta}^{\hat{\theta}} q(\tilde{\theta}) d\tilde{\theta} + q(\hat{\theta})(\hat{\theta} - \theta),$$

which can be expressed as

$$\pi(\theta) - \int_{\theta}^{\hat{\theta}} \left(q(\tilde{\theta}) - q(\hat{\theta})\right) d\tilde{\theta}\ .$$

If $\hat{\theta} > \theta$, the integrand is nonnegative, so $\pi^*(\hat{\theta}, \theta) \leq \pi(\theta)$. If $\hat{\theta} < \theta$, the integrand is nonpositive, but then the integral is nonnegative (since the direction of integration is backwards), so that $\pi^*(\hat{\theta}, \theta) \leq \pi(\theta)$. We know that $\pi^*(\theta, \theta) = \pi(\theta)$, so (1) holds.

Thus conditions (3), (4), (7), and (8) are equivalent to feasibility.

One of the key assumptions in this analysis is that the government does not know the contractor's marginal cost but that the contractor does know this cost. The government does have some insight into this, and this knowledge is represented by a probability density function, which we denote by f. The cumulative distribution function is denoted by F. In this paper, we assume that f is a uniform distribution. The limits of this distribution, which are known to the government, are denoted as θ_0 for the lower limit, and θ_1 for the upper limit.

When the government implements a feasible policy, the expected net gain to the government is

$$\int_{\theta_0}^{\theta_1} \Big(V\big(q(\theta)\big) - p(\theta)q(\theta) - s(\theta)\Big) f(\theta)d\theta.$$

The expected profit for the contractor, from the perspective of the government before θ is revealed, is

$$\int_{\theta_0}^{\theta_1} \pi(\theta)f(\theta)d\theta.$$

Note that the mechanism is established a priori before the contractor's marginal cost is revealed. The government will want the contractor's profit to be as low as possible, but it may need to give it some weight to convince the contractor to participate in the mechanism, as it is possible that the contractor's profit will be low enough that it will not be willing to participate. The authors have seen contractors willing to quit negotiations when terms are not favorable enough for them.

If we then maximize the weighted sum of the government's gain and the contractor's profit using weight α for the contractor's profits, with $0 \leq \alpha \leq 1$, then the objective function is

$$(9) \qquad \int_{\theta_0}^{\theta_1} \Big(V\big(q(\theta)\big) - p(\theta)q(\theta) - s(\theta)\Big) f(\theta)d\theta + \alpha \int_{\theta_0}^{\theta_1} \pi(\theta)f(\theta)d\theta\ .$$

We next work to derive a form for which we can find the maximum. From the profit function, we can write the revenues as the profit plus the cost, i.e.,

$$(10) \quad p(\theta)q(\theta) + s(\theta) = \pi(\theta) + \theta q(\theta) + k.$$

From condition (7),

$$\int_{\theta_0}^{\theta_1} \pi(\theta)f(\theta)d\theta = \int_{\theta_0}^{\theta_1} \left(\int_{\theta}^{\theta_1} q\big(\tilde{\theta}\big)d\tilde{\theta} + \pi(\theta_1) \right) f(\theta)d\theta$$

$$= \int_{\theta_0}^{\theta_1} \int_{\theta}^{\theta_1} q\big(\tilde{\theta}\big)d\tilde{\theta}\ f(\theta)d\theta + \pi(\theta_1) \int_{\theta_0}^{\theta_1} f(\theta)d\theta$$

$$= \int_{\theta_0}^{\theta_1} \int_{\theta}^{\theta_1} q\big(\tilde{\theta}\big)d\tilde{\theta}\ f(\theta)d\theta + \pi(\theta_1)\ .$$

The value of the integrand above is equivalent to the area of the product of q and f over a triangle, in a two-dimensional plane, with θ taking the role of x and $\tilde{\theta}$ taking on the role of y. This is displayed graphically in Figure 9.

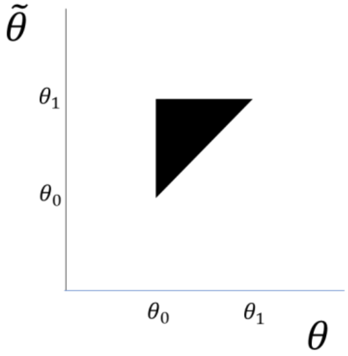


Figure 9. Visualizing the Double Integral.

The diagonal border in the graph is the diagonal line $\tilde{\theta} = \theta$. Since we integrate over $\tilde{\theta}$ first, the limits of integration are θ to θ_1 for the variable $\tilde{\theta}$, and then θ_0 to θ_1 over the variable θ. If we change the order of integration so that we integrate over θ first, the limits of the integration are instead from θ_0 to the diagonal line, i.e., θ.

That is, we can change the order of integration, and the integrand plus the constant term is equal to

$$\int_{\theta_0}^{\theta_1}\left(\int_{\theta_0}^{\theta} f(\theta)d\theta\right) q(\tilde{\theta})d\tilde{\theta} + \pi(\theta_1)$$

$$= \int_{\theta_0}^{\theta_1} F(\tilde{\theta})q(\tilde{\theta})d\tilde{\theta} + \pi(\theta_1)\ .$$

Writing all these tilde's is cumbersome, so without loss of generality we change the notation so that $\tilde{\theta}$ becomes θ (trivial change of variable). Thus, the expression can be expressed as

$$\int_{\theta_0}^{\theta_1} F(\theta)q(\theta)d\theta + \pi(\theta_1)\ .$$

Substituting first (10) and then this result into (9), we find

$$\int_{\theta_0}^{\theta_1}\Big(V\big(q(\theta)\big) - p(\theta)q(\theta) - s(\theta)\Big) f(\theta)d\theta + \alpha\int_{\theta_0}^{\theta_1} \pi(\theta)f(\theta)d\theta$$

$$= \int_{\theta_0}^{\theta_1}\big(V\big(q(\theta)\big) - \pi(\theta) - \theta q(\theta) - k\big) f(\theta)d\theta + \alpha\int_{\theta_0}^{\theta_1} \pi(\theta)f(\theta)d\theta$$

$$= \int_{\theta_0}^{\theta_1} \big(V\big(q(\theta)\big) - \theta q(\theta) - k\big) f(\theta) d\theta - (1-\alpha) \int_{\theta_0}^{\theta_1} \pi(\theta) f(\theta) d\theta$$

$$= \int_{\theta_0}^{\theta_1} \big(V\big(q(\theta)\big) - \theta q(\theta) - k\big) f(\theta) d\theta - (1-\alpha) \left(\int_{\theta_0}^{\theta_1} F(\theta) q(\theta) d\theta + \pi(\theta_1)\right)$$

$$(11) \quad = \int_{\theta_0}^{\theta_1} \left(V\big(q(\theta)\big) - \left(\theta + (1-\alpha)\frac{F(\theta)}{f(\theta)}\right) q(\theta) - k\right) f(\theta) d\theta - (1-\alpha)\, \pi(\theta_1)\ .$$

This is maximized by operating on the demand curve, which means setting the price paid to the contractor as $\theta + (1-\alpha)\frac{F(\theta)}{f(\theta)}$.

The mechanism sets the subsidy as

$$(12) \quad s(\theta) = \theta q(\theta) + k - p(\theta) q(\theta) + \int_{\theta}^{\theta_1} q(\tilde{\theta}) d\tilde{\theta}\ .$$

To see that this is feasible, we have from (7) and (10) that

$$s(\theta) = \pi(\theta) + \theta q(\theta) + k - p(\theta) q(\theta) = \theta q(\theta) + k - p(\theta) q(\theta) + \int_{\theta}^{\theta_1} q(\tilde{\theta}) d\tilde{\theta} + \pi(\theta_1)\ .$$

The subsidy thus requires that $\pi(\theta_1) = 0$, which meets feasibility constraint (8). Feasibility condition (3) is met by the optimal price. Constraint (4) requires that the hazard rate function for f is monotonic. We will only treat the uniform case in this paper, so that the monotonicity condition is met. (Note that if f is not monotonic, additional work must be done. See Baron and Myerson (1982) or Fudenberg and Tirole (1991) for more information.) Thus, the subsidy is feasible, and the Baron-Myerson mechanism is optimal with regard to price and quantity.

We see from (12) that the greater the uncertainty about the cost, the more the government pays to the contractor via subsidy. This is because the greater the uncertainty, the greater the difference between θ and θ_1. Note that if the government knew the contractor's cost with certainty, the price per unit paid would be the marginal cost θ; total price paid to the contractor would be $\theta\, q(\theta)$, and the subsidy would be $\theta q(\theta) + k - \theta q(\theta) = k$, which is the contractor's fixed cost. Thus, the government would cover the contractor's fixed and marginal costs and set profit to zero. Thus, $\int_{\theta}^{\theta_1} q(\tilde{\theta}) d\tilde{\theta}$ is a measure of the value of knowledge of the contractor's marginal cost.

To apply this mechanism to the monopolistic contractor example, assume that the government knows the fixed cost but does not know the marginal cost. However, the government knows the marginal cost is between \$6 and \$12 for each unit. Thus, the cost is modeled as a uniform probability distribution, with lower bound equal to \$6 and upper bound equal to \$18, that is $f(c) \sim U[6,18]$. The government will cover the fixed cost, as before, but now will give the contractor a value above the cost, keeping some of the surplus for itself, and sets $\alpha = 0$.

In this mechanism, the contractor will report its marginal cost, θ. The government will then pay the contractor

$$v(\theta) = \theta + \frac{F(c)}{f(c)}.$$

In the case of a uniform distribution this is

$$v(\theta) = \theta + \theta - L = 2\theta - L.$$

Since the actual marginal cost is $10, the government pays the contractor *2*$10-$6=$14* for each unit. At this price, the demand curve indicates that the government wants 18 units. It will purchase 18 units at $14 each. Without the subsidy, the profit for each unit would be $4 for each unit. However, the government takes back a significant amount of this profit in form of a negative subsidy, as demonstrated graphically in Figure 10.

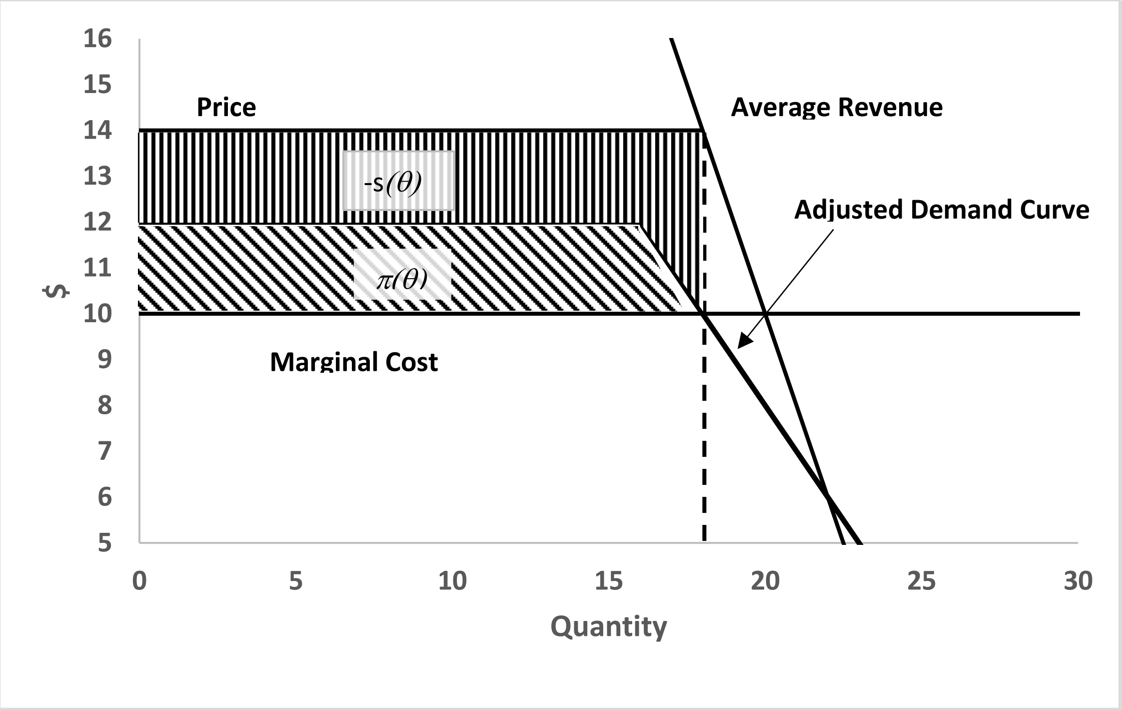


Figure 10. Graphical Example of the Baron-Myerson Mechanism.

With the negative subsidy, the total profit for the contractor is cut to $33. Thus, the net average marginal unit price is equal to 33/18, which is approximately $1.83. Since in this example no weight is given to the contractor's profit, the value of the information is equal to the profit, in this case $33.

See Table 2 for a comparison of no mechanism with the Loeb-Magat and Baron Myserson mechanisms. Loeb-Magat results in higher quantity but does nothing to shrink monopoly profits, while Baron-Myerson increases quantity while cutting profit substantially.

Mechanism	Quantity	Profit	Profit/Unit
None	10	$200.00	$20.00
Loeb-Magat	20	$400.00	$20.00
Baron-Myerson	18	$33.00	$1.83

Table 2. Comparison of the Base Case with the Two Mechanisms.

Since this is all determined upfront, the government could set up the contract to make a payment that is net of the subsidy, thus avoiding the transaction costs of collecting a tax after making a payment. The contractor may not be willing to sign up for this deal, so the government may have to negotiate an α-value that is positive. A key part of the implementation will be to find an α-value that contractors will accept. As monopolists in an unregulated industry, they can refuse to do the work; they have political power since the large defense contractors have lobbyists in D.C.; and as unregulated monopolists in production, they are used to "living high on the hog," to use a colloquialism from the Southeastern United States.

Practical Challenges

If demand curves are inelastic, that is, the demand does not change much as the price changes, then this analysis is all for naught. However, Howarth has presented evidence that demand curves across weapon systems of the same type are relatively elastic. (Howarth 2018) What remains to be shown is whether the demand curve for a single weapon system is elastic as well, or if the quantities are driven purely by security concerns. However, there are questions about whether we can know the demand curve. (Lofgren 2018)

The government must build trust and have the discipline to stick to the rules of the mechanism. There will be a temptation, once the contractor reports its true cost, for the government to want to eliminate all contractor profit. There is a significant amount of turnover in DoD leadership positions, due to rotation of military program managers and changes in political leadership. Thus, there will be a temptation for new leadership to upend policy. Making a change to take advantage of a contractor's revelation will only work once, after that the contractor will refuse to participate in the mechanism.

Summary

We have shown that there is limited competition in the market for weapon systems and aerospace. Pure monopoly is prevalent in production, as the government typically does not purchase technical data rights or extend competition past the signing of a contract for initial design. This leads to higher prices and lower quantities. The higher prices that government leadership decries is the result of this lack of competition. Simply advocating more competition without either breaking up the oligopolies or paying for technical data rights will severely limit the amount of competition. In the long term, the government should work to make the contractor market more competitive. In the short term, the government can use mechanisms, such as those presented in this paper, to achieve higher output at lower cost. The use of the Baron-Myerson mechanism has potential to achieve the goal of better buying power.

The US government has regulations that require cost reporting; however, determining the true costs of production are difficult. The lack of insights results in higher prices for the government. Continuing to improve cost data reporting for all contracts is a major step in the right direction. There will always be some uncertainty in cost, since these are systems that take years to build. Reducing concurrency of development and production will decrease production cost risks and is recommended.

Encouraging competition by commercial firms like SpaceX and Blue Origins has the potential to save money. Revamping antitrust laws and critically examining potential mergers and acquisitions that could limit competition need to be a government priority. Changing acquisition laws to give the government data rights to the project it pays to develop will also help enable competition before production, ending the monopoly markets for production in the Department of Defense.

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