The Organization of Production: Moral Hazard and R&D

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ABSTRACT

We model technical innovation of a final good at the subcomponent level. Research and Development efforts are undertaken on subcomponents, incrementally enhancing the technological inputs to the final good. Through observation of actual R&D procurements, we identify the principal and agents appropriate for such innovation. Two categories of agent, the conventional profit seeking agent and a performance seeking agent, are identified. A principal who jointly values the capabilities of the subcomponent undergoing R&D and the funds available for purchasing other subcomponents to the final good is identified. The principal does not have a transferable utility function. We characterize optimal R&D production organization between such a principal and each type of agent. In addition to the importance of the information environment between principal and agent, the motivational properties of the principal and agent significantly affect the form and existence of optimal R&D procurement. We draw insights for both private and public sector industrial organization.

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Chapter 1: The Role of R&D in Production Organization

Understanding the production organization of a final good assembled from numerous subcomponents is of obvious significance. Though an assembly line comes to mind, the image is of little relevance, for an assembly line is the process through which already produced subcomponents are combined in a routine and monitorable manner. The true question of interest in production organization is how subcomponent production is organized. Three examples are evocative:

> Most major automobile manufactures produce their own engines whereas not a single airplane manufacturer produces jet engines.
>
> Many automobile companies produce the suspension subcomponent for their entrants in the sports car market yet purchase the suspension system design from Lotus of England.
>
> Producers of finished food products purchase NutraSweet from the corporation that holds the patent whereas Mashushita produces its own compact disc systems via a license purchased from Sony and Phillips.

These examples involve technological innovation in the subcomponents that constitute the final good. The fundamental effect of technological progress on production is obvious and well accepted. What are not obvious are the reasons behind the myriad organizational structures between innovator and final producer that we observe. Subcomponents may be innovated and produced under the management of the final good producer, innovated by one entity and produced by the final good producer, or innovated and produced by one entity and transferred to the final good producer. The organization of subcomponent innovation, hereafter referred to as Research and Development (R&D), is critical to production organization, yet the forms chosen for R&D organization are not adequately explained by either the existing Industrial Organization or Optimal Contacting literatures. In this thesis we attempt an adequate treatment of R&D subcomponent production organization. A quick review of established theory motivates our approach.

Coase's observation that production is vertically integrated to the degree that the marginal cost of so doing is below that of market contracting provides a unifying paradigm yet so borders on tautology that little can be specifically explained.[1] Alchain's and Demsetz' corollary that production is vertically integrated until the *cost of management* forces the marginal cost of internal production to exceed that of market procurement adds little except to suggest that production efficiency within a firm is degraded when subordinates can conceal their inputs to production, thus extracting a rent from management.[2] When subordinates behave this way it is referred to as moral hazard. Williamson expands on Alchain's, Crawford's, and Klein's observation of the significance of bilateral monopoly in complex subcomponent production by illustrating the effects of moral hazard in both internally organized and market contracted production.[3,4] Past analytical research has concentrated on principal/agent models of single component production with no work expressly considering the effects of subcomponent production.[5]

A more useful characterization of the motivating reasons for production organizations can be attained by analyzing subcomponent production -- emphasizing the organizational significance of the goals of the final good producer and the goals of subcomponent producers. In this thesis we examine subcomponent procurements that require research and development (R&D), a process particularly prone to the influence of moral hazard due to the probabilistic nature inherent in innovation. The effects of the type of final product, the interests of the principal, and the interests of the potential agents are considered in characterizing optimal organizational arrangements (contracts).

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[1] Ronald H. Coase, "The Nature of the Firm," *Economica*, New Series, vol. 4, 1937.

[2] Armen A. Alchain, Harold Demsetz, "Production, Information Costs, and Economic Organization," *The American Economic Review*, vol. 62, no. 5, 1972.

[3] Benjamin Klein, Robert G. Crawford, and Armen A. Alchain, "Vertical Integration, Appropriable Rents, and the Competitive Contracting Process," *The Journal of Law and Economics*, vol. 21, no. 2, 1978, page 299.

[4] Oliver E. Williamson, "Transaction-Cost Economics: The Governance of Contractual Relations," *The Journal of Law and Economics*, vol. 22, no. 2, 1979.

[5] The works of Laffont, Tirole, Hölmstrom, and others represent analytical treatments of simple optimal contracting in the presence of moral hazard. The classic moral hazard optimal contracting literature is examined in greater detail in Chapter 4.

One of the primary goals of this research is to provide practical insight into why and how production, particularly innovation, should be organized; thus, it is natural that case studies be examined for both guidance and credibility. Rather than cataloging the characteristics of existing production organizations under the assumption that 'to be is to be optimal', we attempt to uncover the principal/agent genesis of production organizations by examining the pathology of a production organization that was rendered non-optimal due to poor acknowledgment of moral hazard. Production of the Mars Observer planetary mission (launched in September of 1992) required the organization of an array of agent interests within a multiple component R&D production process.[6] Studying the evolution of the subcomponent contracts for Mars Observer reveals a non-optimal production organization that illuminates the importance of moral hazard, and, thus, the relevance of principal/agent concerns in R&D production organization.

The thesis is organized as follows: We first study the physical nature of the Mars Observer production process, the motivational differences between the principal and the different agents, and the historical evolution of subcomponent production organization. We proceed through a structured, analytical modeling of the types of production organization highlighted in the Mars Observer experience with the intent to characterize general optimal contracting arrangements. Using this analytical structure the Mars Observer experience is assessed, highlighting the ramifications of contracting without regard for moral hazard. Thereafter, general principles of optimal R&D subcomponent production organization are applied to several examples of existing and potential final good production. The thesis concludes with a perspective that supports an understanding of why production in a complex economy is organized as it is and how certain production might be better organized.

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[6]The same can be said of all 'Big Science' Projects.

Chapter 2: The Pathology of Mars Observer Production Organization

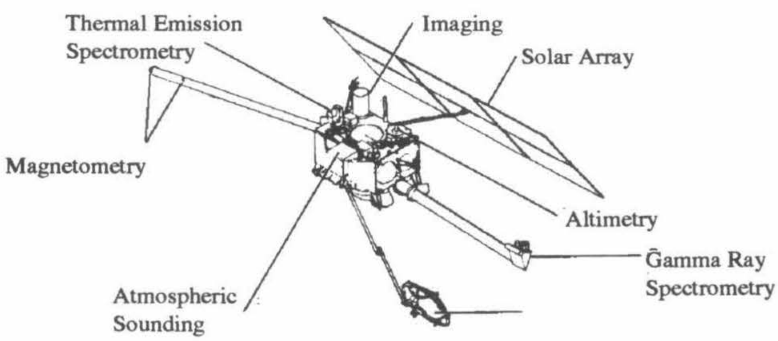
2.0 Description of the Mars Observer Mission

The two Viking missions to Mars in the mid- to late 1970's were designed to conduct detailed measurements at two points on the Martian surface, with orbital imaging employed primarily to assess potential landing sites. The results of the orbital imaging and the scientific information from the two landing sites raised substantial questions about the geologic and climatologic natures of Mars on a global scale. These questions led to the Mars Observer mission which was authorized by the Office of Management and Budget (OMB) in October 1983 (later by the U.S. Congress) and delegated to the Jet Propulsion Laboratory (JPL).

The intended final good from the Mars Observer mission is new information about Mars. To produce this final good, a number of subcomponents have to be produced, assembled, and operated: experiments (conducted using various instruments) and experiment support systems (transport, power, communications, etc...). Selection of the experiment and support system producers occurred in April 1986 with substantial funding beginning in mid-1986.

Figure 2.1 illustrates the Mars Observer spacecraft and experiments as launched on September 25, 1992. The price of the mission has been recorded at approximately $530 million (1992$) over the period from October 1983 to October 1992. The original

Figure 2.1: Mars Observer Spacecraft and Experiments

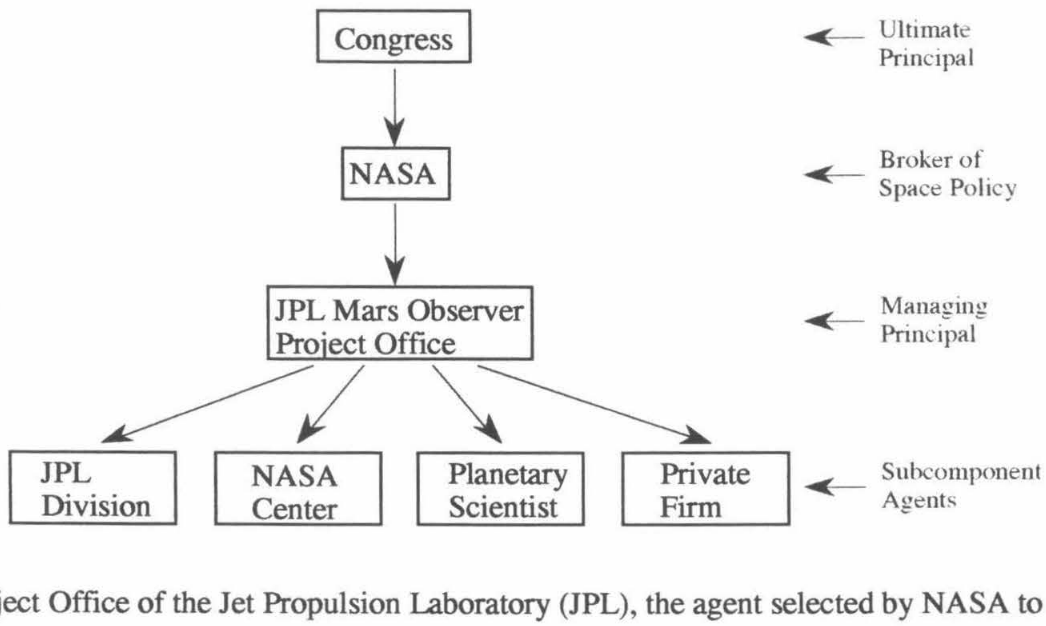


budget for the mission was approximately \$250 million (1992\$). The experiments shown are less ambitious than those that were selected in 1986. When launched, the spacecraft was capable of transporting more mass and supplying more power than was required even though several of the experiment subcomponents had made mass and/or power reductions that resulted in decreased capabilities and/or cost increases. This physical resource surplus indicates a production organization that was ex post sub-optimal, a conclusion heightened by the substantial price overrun for the mission.

2.1 Management Hierarchy: Definition of Players

Production of the Mars Observer mission was organized within a hierarchy leading from the funding source to the producers of the various subcomponents as illustrated in Figure 2.2. Between Congress and the Subcomponent Agents rests NASA, the agency of the Executive authorized to conduct the mission, and the Mars Observer

Figure 2.2: Authority Hierarchy for the Mars Observer Mission



Project Office of the Jet Propulsion Laboratory (JPL), the agent selected by NASA to organize mission production. The Project 0ffice acts as a primary source of advice to NASA when critical subcontractors are selected and is responsible for negotiating and implementing all subcomponent contracts. Given this status, the Project Office can be thought of as the Managing Principal, a type of intermediate agent to whom is delegated the responsibility of pursuing the wishes of the Ultimate Principal. The standard information asymmetry, which creates an environment for moral hazard, pertains; namely, each Subcomponent Agent has clearer information about the production status of their subcomponent than does the Managing Principal.

Figure 2.2 indicates four general types of agent for the various subcomponents. These agent types are most tellingly distinguished by their differing interests relative to participation on the mission:

> A **JPL Divisional or NASA Center Agent** can be motivated by the performance of their subcomponent; however, institutional interests commensurate with maintaining or advancing their position within their parent organization may cause such an agent to value funding independently. For example, the wish to maintain or win some other contract may encourage the reallocation of funds, quality labor, or physical resources away from the particular subcomponent.[7]
>
> Inclusion as an experiment subcontractor can fundamentally affect the career of a planetary scientist; thus, a **Scientist Agent** can be thought of as primarily motivated by the performance of his experiment.[8] This will put him in partial agreement with the Project Office which values some balanced measure of performance from all of the experiments.[9]
>
> Ignoring any repeated game effects, the **Private Firm Agent** will be a profit seeker.[10] He has no fundamental concern with the performance of his subcomponent and wishes to charge as much as possible for whatever work he does or can claim to have done.

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[7]The standard organizational arrangement between a NASA-funded Project Office and a NASA Center or JPL Divisional agent legally forbids the agent from directly profiting from the arrangement. However, such an agent has numerous non-performance uses of funding including: the number of assigned employees, office equipment, and labor/capital allocations among a project portfolio.

[8] Planetary Science missions to any one destination are infrequent and, from a career standpoint, not easily foreseen. A scientist agent for an experiment may shape the type, quality, and dissemination of the data from his experiment. Further, he is often granted a one year monopoly right to data from the moment it is received. Thus, presence as an experiment agent has a fundamental career-long worth to a scientist.

[9]Graft is still a possibility; however, the assumption is that a scientist's long-term carrier motivation to lead his field through a successful outcome from his experiment will dominate short-term motivations to commit graft. The prohibition on profit is accompanied by a prohibition on loss -- the scientist may not be compelled to absorb any production costs even if his subcomponent fails to operate.

[10]Unlike planetary scientists for whom planetary missions represent almost all demand for their wares, private aerospace subcontractors have many other markets; therefore, any rationale that a reputation effect will throttle moral hazard profiteering by a private firm agent is suspect as the NASA 'market' and the standard aerospace market may be too dissimilar for a 'bad' NASA reputation to have any binding effect..

It will be assumed that the interests of the ultimate principal, Congress, can be fully characterized by two related qualities of the mission: the price paid (funds appropriated) and the performance attained.[11] It will further be assumed that the 'contract' between the Congress and the Project Office (through NASA) appropriately rewards or punishes the Project Office for managing the mission with respect to the interests of the Congress.[12] Thus, it is reasonable to assume that the Project Office will organize the production of mission components to maximize the price/performance outcome relative to congressional values, with appropriate compensation to the Project Office. From this perspective the differences between the interests of the Project Office and the Agents can be highlighted:

> A **JPL Divisional or NASA Center Agent**, by valuing the performance from its experiment, will value a subset of the overall performance measures valued by the Project Office. Partial agreement implies partial disagreement; thus, unbridled pursuit by the agent to enhance the performance of its experiment may un-balance the overall measure of performance valued by the Project Office. Further moral hazard is present because of this agent's independent valuation of other uses of funding which is in direct opposition to the Project Office's interest in maximizing a balance of performance and mission price.
>
> A **Scientist Agent**, by valuing the performance from its experiment, may pursue funding in a manner at odds with the overall performance interests of the Project Office. Also, any valued use of funds other than experiment R&D may put this agent at odds with the interests of the Project Office.
>
> In a wholly conventional and obvious fashion, the interests of the **Private Firm Agent** are completely opposed to the interests of the Project Office.

Several clarifications should be placed on agent status that provide insight into the many tiered complexity of this R&D production process and a clearer justification for considering the Scientist Agent to be a distinct type from the JPL Divisional and NASA Center Agents. An agent for a particular subcomponent will most likely have

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[11]Performance will be considered as some measurable increase in the body of scientific knowledge about the target of the mission. As this scientific knowledge is multi-disciplinary, 'balanced' increases are assumed to be preferred to increases skewed toward one discipline. An indication of a preference for 'balanced' science return from a mission can be inferred from the experiments selected.

[12]This assumption simplifies the examination of the organizational relationships between the sub-contractors and the managing principal; however, the assumption is strong and arguable.

subcontractors of its own. Further, one of these lower level subcontractors can be a member of one of the four general agent types. For example, a NASA Center may be under contract to the Project Office to produce the instrumentation for a particular experiment for which the Center subcontracts to a chief scientist and several private firms. In an additional complication, two of the possible agent types are subdivisions of organizations that 'out rank' the Project Office; i.e., a JPL Division is a pre-existing subsection of JPL and a NASA Center is a constituent part of NASA with equal overall hierarchical position to JPL. Thus, the actual authority wielded by the Project Office over agents of these two general types is questionable. Strong institutional interests at NASA or JPL might work to countermand Project Office directions. The potential ramifications of 'out ranking' the Managing Principal requires distinguishing the Scientist Agent from the JPL Divisional or NASA Center Agent.

The initial organization of subcomponents and agents for Mars Observer is provided in Table 2.1. It should be noted that the vast majority of the subcomponents of the mission were subcontracted; almost none of the actual design and production was to be directly supervised by the Project Office.

Table 2.1: Intitial Organization of Subcomponents and Agents

Subcomponent	Agent	Agent Type
Spacecraft	Astro Space Division of RCA, later aquired by General Electric	Private Firm
Altimetry	Goddard Space Flight Center	NASA Center
Atmospheric Sounding	JPL Technical Divisions	JPL Division
Physical Composition: Mapping Spectrometry	JPL Technical Divisions	JPL Division
Physical Composition: Gamma Ray Spec.	Goddard Space Flight Center	NASA Center
Physical Composition: Thermal Emission Spec.	Arizona State University, Dr. Christensen	Scientist
Imaging	Arizona State University, Dr. Malin	Scientist
Magnetometry	Goddard Space Flight Center	NASA Center

2.2 Initial Organization of Production

Initially, the Spacecraft contract was comprised of two distinct and sequential payment streams: a pre-determined series of payments leading up to launch, followed by a stream of contingent payments that would be transferred to the contractor over the life of the mission if the spacecraft performed properly. This type of contract was designated as a Fixed Price Performance Award contract. By using a fixed price contract for a set of pre-defined performance requirements the spacecraft agent was to have no opportunity to seek additional funding from the Project Office for any actual or claimed 'unlucky' occurrences. Such actions by the spacecraft agent were to have been eliminated by, in effect, agreeing to a subcomponent price sufficiently high to allow the agent to *comfortably* self-insure against 'unlucky' outcomes while providing no incentive to misrepresent progress.

All experiment subcontracts were to be margin contacts, a contract that explicitly recognized the unknown tradeoffs between performance and price at the start of an R&D process: An experiment agent was provided with an initial funding allocation to start R&D production. Subsequent funding allocations were provided in accordance with the price/performance tradeoffs for the technologies that emerged from the early stages of R&D production. A margin pool was to be held by the Project Office from which these subsequent allocations would be made.

The policy of margin management was standard practice and was considered analogous to an insurance pool guarding against the incidence of 'bad luck' attendant to R&D in state-of-the-art instrument production. To a point, the more 'unlucky' the initial research efforts, the greater the subsequent margin funding. Moral hazard was to be guarded against by monitoring the purported 'bad luck' necessitating the margin allocation request. Standard margin policy does not set firm rules regarding the extent to which any agent may draw from the margin pool relative to the expressed needs of other agents. Margin allocations would be decided in real-time by the Project Office and would not be subject to any prior agreements.

Obviously, all of the experiments, once the instruments are built, are integrated with the spacecraft and propelled to Mars. Consequently, the mass, power usage, and volume that the instruments require from the spacecraft represent resources which must be produced in concert with the experiments if the assembled mission is to result in the final good desired; namely, science return from Mars. As with funding, all physical experiment resources were organized with contracts featuring centrally held margin pools and standard margin management.

When an experiment receives changes in physical resource margin allocations, the contracted configuration of the spacecraft must often change. This is most obvious when mass margin allocations affect the center of mass for the assembled mission, requiring the addition of counter-balancing 'dead weight' and/or the repositioning of numerous components. Contractually, such a change is the fault of the Project Office; thus, the spacecraft contract must be reopened and the spacecraft contractor must be compensated for the change. Through this dynamic, the Fixed Price Performance Fee contract, and its laudable qualities countering agency concerns, can be rendered void. The contract can effectively become a cost-reimbursable contract with price increases driven by experiment margin allocations and moral hazard profiteering by the spacecraft agent.

This possibility did not go un-noted by the Project Office. At the earliest stage of Mars Observer production organization design, an instrument module, produced by JPL, was to provide the physical interface between the experiments and the spacecraft. The total of all physical resources used by the instrument module and all instruments integrated on it was to be fixed with the Project Office allocating resource margins defined within this fixed total. In this manner, the spacecraft contractor would see a credibly fixed interface and know he was truly subject to a fixed price contract. But, the JPL Project Office was concerned over the funding and physical resources that an instrument module would require at the expense of other mission subcomponents. This concern resulted in the deletion of the module from the mission.[13] The recognition that this might cause incentive problems is apparent from the following view expressed by the Assistant Laboratory Director for Flight Projects during the period when module deletion was being discussed:

> "This is a sticky wicket. Somehow we have to maintain the concept of a module thru the Bus (Spacecraft) selection process. ... The main worry I have in abandoning the idea of the payload module is that we might lose some element of control over the experimenters' appetites (for funds, mass, power, etc..) which the spacecraft contractor would be only too happy to satisfy -- and submit the bill later."[14]

Still, the instrument module was deleted, with no compensating changes made to any other parts of the production organization design.

The spacecraft contract allowed Project Office changes via a mechanism called the unilateral modification -- the Project Office unilaterally directs the contractor to make a change to the contracted effort. The unilateral modification mechanism contains a 'time is of the essence' clause which allows the Project Office to authorize the contractor to begin work on the modification before the two parties have agreed on a price for the modification. At the time that proposals were requested from potential subcontractors, the module had been deleted and the planned contracting organizations, including the unilateral modification mechanism, were public knowledge. Thus, bidders for the spacecraft contract could easily assume that the experiment margin management policy would result in substantial unilateral modifications to the spacecraft contract, with the selected contractor in a monopoly position at the time of price re-negotiation. Substantial extra profit potential therefore existed because of the non-fixed nature of the Fixed Price Performance Fee contract. An additional ramification of the unilateral modification mechanism is that since all potential spacecraft contractors knew that, if selected, they

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[13]MGCO Project Management Report, March 23, 1984.

[14]W. Giberson (JPL ALD), Handwritten note on a copy of JPL Interoffice Memorandum of W. Purdy, re: 3/14/84 RFP Meeting with Code EL, March 9, 1984.

were unlikely to have to deliver the bid spacecraft at the bid price, there is little reason to believe that the bid prices represented reliable cost or comparative advantage information.

With the exception of Magnetometry, all of the experiments were to use instruments that represented state-of-the-art designs This was reasonable because the state-of-the-art for Mars instruments was defined by the early 1970's technology used on the Viking missions. Commensurate with the developmental status of their instruments, most of the agents requested funding for some form of prototyping; from concept-testing breadboarding to full engineering models.[15]

The Mars Observer Mission had been 'sold' to the Office of Management and Budget and then later to the Congress as a more cost effective way of undertaking planetary exploration featuring the use of existing "off-the-shelf" technologies, private industry, rapid production, and a price tag of $250 million (1992$). When the subcomponent contracts were signed (most by late 1986) the Project Office was under intense pressure from NASA to constrain the estimated total cost of the mission to $250 million (1992$). Thus, all tasks not specifically related to production of flight hardware were disallowed.[16] By disallowing all prototyping, monitorable indicators of progress on the various experiment R&D efforts were consciously discarded by the Project Office.

On November 13, 1986 the Project Office recommended to NASA that contracts be initiated with all of the experiment agents at levels of funding that, when added to the spacecraft fixed price, totaled less than $250 million (1992$). However, the Project Office also recommended that NASA and the Congress provide additional funds to cover

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[15]That such requests had to be made is suggestive of the type of contractual relationship between the Project Office and the instrument agents -- detailed production plans had to be submitted with all aspects subject to Project Office approval. Thus, when the Camera (Imaging) agent reported that through the use of a lighter and stronger casing material he could increase the camera primary mirror from 25 cm to 35 cm, substantially increasing performance without increasing total mass or cost, he had to request permission to do so. [*Mars Observer Project Management Report*, June 26, 1986.]

[16]*Mars Observer Project Science Group Meeting Minutes*, First Meeting, F. Palluconi, and Section L, April 23 and 25, 1986.

the developmental nature of the instruments.[17] This was a clear admission by the Project Office that the subcontracted prices were not credible.

The potential implications of the margin management structure employed to organize Mars Observer experiment production are straightforward. Because of moral hazard, incidences of bad luck will be reported as the basis for a margin allocation request if the agent judges the current environment (size of margin pool, disposition of Project Office, etc....) to be conducive to maintaining experiment status. Incidences of good luck will go unreported if the agent feels that a reverse margin policy would commandeer his good fortune to compensate for someone else's purported misfortune. Thus, resource savings from good luck will be (i) retained by the agent as insurance against future bad luck, (ii) used to increase performance (by a performance motivated agent), or (iii) transformed into monetary savings and pocketed (by a funding motivated agent). Knowing that his estimates need not be credible and that he will probably be at least partially compensated in the future with margin allocations, an experiment agent can willingly submit or agree to 'optimistic' initial estimates. Further, the agent is relieved of the need to manage its production organization in as rigorous a manner as if its resource estimates were somehow binding. Cost increases over initial cost estimates were inevitable.

The experiment and spacecraft agents were selected in the period immediately after the Challenger disaster; NASA funding was being restructured and launch dates and conditions for future missions were undergoing substantial re-planning. In the pre-Challenger plan, Mars Observer was to be launched in August 1990; however, by August 1986 the decision had been made to postpone the launch until September 1992. For reasons beyond the purview of this thesis, the Project Office had to publicly claim that Mars Observer was being actively organized for a 1990 launch while at the same time it

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[17] *Mars Observer Project Management Report*, November 20, 1986.

had to manage the project in accordance with a 1992 launch.[18] On April 14, 1987 the postponement to 1992 was officially ordered. By this date, contracts with all subcomponent agents had been initiated along the lines described above.

Based on the additional two year wait for information return and using the consequences of the Challenger disaster for fiscal cover, a six month effort to redefine Mars Observer for 1992 commenced in May of 1987. Risk of failure was to be lessened by increasing redundancy where ever practical. All experiment instrument designs were re-evaluated to enhance the science return from the mission. The spacecraft contractor was asked, via the unilateral modification process, to redesign and accommodate all of the enhancements as they were approved.

At this point, approximately 5% of all eventual funds had been allocated toward the subcontracts, no actual hardware had been produced or tested, and most designs were incomplete. Although the specific subcomponents had yet to be agreed upon, the participants had been contracted with and the basic structure of the contracts did not change. The situation can be seen as a collection of bilateral monopolies with the Project Office as a monopsonist party to a set of monopolist suppliers. The appropriate description of the initial organization of Mars Observer production is:

> Mars Observer production was initially organized as a set of bilateral monopolies governed by one very un-fixed, fixed price contract and a set of cost-reimbursable contracts that were to be implemented under the margin management process.

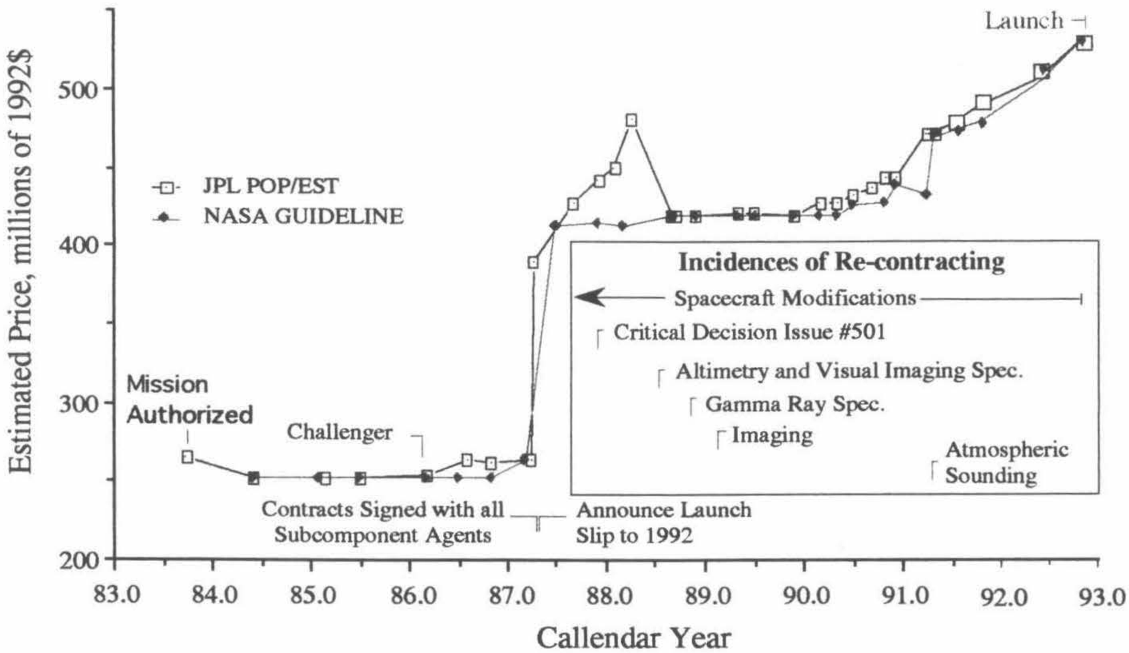
2.3 Evolution of Subcomponent Development

After the launch delay was official, the reported estimated costs escalated quickly and dramatically as shown in Figure 2.3. By November of 1987, estimated costs were so

[18]Charles Polk, *Mars Observer Project History*, JPL D-8095 (internal document), December 1990.

great that NASA refused to support the project as organized and issued Critical Decision Issue (CDI) #501, requesting information from the Project Office on ways to reorganize (re-contract) the mission to reduce the estimated cost. This led to the mission descope decision of September 1988 in which the mapping spectrometry experiment was deleted from the mission and the instrument for conducting the altimetry experiment was downgraded from a radar altimeter to a laser altimeter, with a different agent and contract.

Figure 2.3: Mars Observer Price Estimate History



The September 1988 re-contracting was the first of several changes made to the bilateral monopoly contracts over the next four years, mostly characterized by changes in the agents contracted to manage the subcomponents. Figure 2.3 indicates the timing and identity of these re-contracting steps: Substantial experiment re-contracting occurred in distinct steps while spacecraft re-contracting occurred incrementally over many unilateral modifications. The remainder of this section will briefly describe the changes in agents, motivations, and production organizations (contracts) that accompanied the re-contracting actions indicated in Figure 2.3.

Spacecraft Re-Contracting

The spacecraft contract was modified from 1988 through 1992 by a series of unilateral modifications issued to accommodate the growing resource demands of the instruments and the growing demands of the Project Office to enhance expected performance. As a rule, the charged price of later modifications exceeded the prices that the Project Office initially expected based on earlier modifications.[19] Increasing expenditure combined with concern over expected performance (quality) led the Project Office to increase JPL on-site monitoring of the spacecraft contractor and to impose JPL production practices on the contractor.[20] All designs, production processes, and inspection specifications had to be reviewed and approved by the Project Office. Hence, spacecraft production management was partially internalized by the Project Office. Rather than subcontract for a spacecraft, the Project Office arranged to 'Rent a Firm' to produce a spacecraft.

Altimetry Re-Contracting

The altimetry subcomponent to science information was initially to be implemented with a radar altimeter. The radar altimeter was eliminated and replaced by a laser altimeter as part of the 1988 re-contracting response to NASA CDI #501. Like the radar altimeter, production of the laser altimeter was managed by NASA's Goddard Space Flight Center. However, the individuals directing the production were different and the contract with the Project Office was fundamentally different -- the laser altimeter would not be produced under a margin management, cost-plus contract. Rather, $11 million (1992 $) was allocated within which the altimeter team was free to make all performance,

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[19]The hardening of the spacecraft contractor's bargaining position as the project progressed is hardly surprising. The nearer to completion, the more expensive it would be to replace the spacecraft contractor with another contractor. Perhaps more significant, the nearer to completion, the more money Congress had 'sunk' into the mission and the less credible is any threat by the Project Office to delay, suspend or terminate the contract.

[20]At no point was an increase in post-launch performance incentive payments implemented rather than these increases in monitoring and intrusion. [see Chapter 6 for a discussion of the ramifications of this]

cost, schedule, and quality tradeoffs that it felt necessary. Only three restrictions were placed on the development effort:

- Interface requirements with the spacecraft must be met.
- If it appeared that the $11 million allocation would be exceeded, production of the laser altimeter would be terminated.
- If it appeared that performance would drop below some minimum level, production of the laser altimeter would be terminated.

Additionally, the individuals responsible for the laser altimeter knew that success would save Goddard's position relative to the science output of the mission; thus, career enhancing performance, though contractually a residual to price, figured in the motivation of the new altimetry subcomponent agent.

Atmospheric Sounding Re-Contracting

Within one year of the 1988 mission descoping, the Project Office was so seriously concerned about the magnitude of eventual margin requests by the JPL Divisional Agent responsible for the atmospheric sounding experiment that it considered downgrading the performance of the experiment.[21] Nevertheless, repeated discussions between the Project Office, the Divisional Agent, and upper JPL management resulted in the continuance of the initial contractual relationships.[22] Margin allocations mounted until the atmospheric sounding experiment was consuming the vast majority of the margin pool. Even at this point, approved margin funding was far less than the requests made by the JPL Divisional Agent In May of 1991, the initial subcontract was terminated and direct production management was internalized with the Project Office. Production was suspended so that existing funds could be reallocated to the other instruments while additional funding was solicited from NASA for the atmospheric

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[21]*Mars Observer Project Management Report,* July 28, 1989, page 3Ca.

[22]JPL Interoffice Memorandum from David Evans, Mars Observer Project Manager to Kane Casani, JPL Division Manager responsible for the Atmospheric Sounder, March 20, 1990; and JPL Interoffice Memorandum from David Evans and Kane Casani to John Casani, Assistant Laboratory Director for Flight Projects, June 11, 1990.

sounder.[23] Once additional funding was in place, the Project Office directed a 'catch-up' production path resulting in the late arrival of the instrument for integration on the spacecraft.[24]

Gamma Ray Spectrometry Re-Contracting

According to at least one analysis, the gamma ray spectrometry experiment barely escaped elimination in the 1988 mission descoping.[25] Funding and physical resource margin requests by the Goddard agent became an increasingly serious problem. The Project Office considered the agent to be unresponsive to requests for information, direction, or concerns over the course of subcomponent production. The Project Office strongly requested and eventually received a restructuring of the effort within Goddard with the responsible agent being replaced and the efforts being reassigned to another section of Goddard.[26]

Imaging Re-Contracting

The imaging experiment was initially contracted to a scientist agent who was a faculty member at an American university. This is the standard arrangement when the subcomponent agent is a scientist. In this arrangement, part of the funding allocated to the agent is absorbed by the sponsoring university for staff benefits, facility use, etc. In this instance, the scientist agent became disaffected with the level of support that his university was willing to supply.[27] Believing this support to be inadequate, the agent

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[23]*Mars Observer Budget Status Report,* presented to Dr. W. Huntress, March 6, 1991, GEC-35, 36; and *Mars Observer FY91 3rd Quarterly Review*, May 16, 1991, GLR-4.

[24]Late arrival for integration violated the spacecraft contract and required, of course, that a unilateral modification be issued by the Project Office to cover the costs of late integration.

[25]See Charles Polk, 1990.

[26]Official JPL letter from John Casani, Assistant Laboratory Director for Flight Projects to Dr. James H. Trainer, Associate Director, NASA/Goddard, November 17, 1989; *Mars Observer Project Management Report*, October 26, 1989, page 3Ca; *Mars Observer FY90 1st Quarterly Review*, December 5, 1989, page DDE-9; *Mars Observer Project Management Report*, December 21, 1989, page 2A1b.

[27]Official JPL letter from David Evans, Mars Observer Project Manager to Marius B. Weintreb, NASA Program Manger for Mars Observer, July 5, 1990.

internalized the support functions normally subcontracted to the sponsoring university by terminating his position with the university, forming his own corporation, and managing the support functions through this corporation.[28] This was possible as the 'property right' to the experiment contract with the Project Office was vested with the contracted scientist agent and not with his university. During and after this bit of agent inspired re-contracting, NASA dictated the allocation of substantial additional funds to the imaging experiment due to renewed emphasis on Mars exploration and the attendant interest in imaging products. Thus, re-contracting was also directed from above. The imaging instrument none-the-less required substantial margin allocations; however, neither the subcontracted agent nor the contract form were altered.

Commentary

Of the major subcomponents, fundamental re-contracting was carried out for six of the eight. Such re-contracting was characterized by a change of agent, a change of contract form, or the outright elimination of the subcomponent. Among the science gathering subcomponents, only the thermal emission spectrometry experiment and the relatively non-developmental magnetometry experiment escaped re-contracting.

2.4 Production Outcome

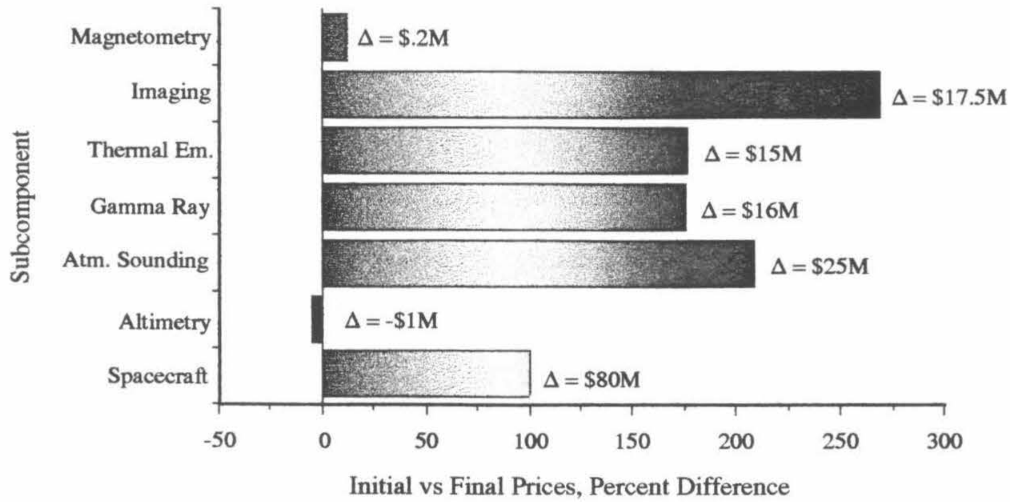
Given that the final product being purchased is scientific information about Mars, the actual outcome of production does not yet exist as of today. However, all of the physical hardware intended to supply the subcomponents for this scientific information have been assembled and sent on their way to Mars. Thus, the production process through final assembly can be analyzed as a proxy for final product analysis if we assume that the hardware will perform as advertised.

Figure 2.4 compares the reported estimated cost of each of the subcomponent contracts, when the conditions of bilateral monopoly were initiated, with the final

[28]E-mail message from Dr. Michael C. Malin, Principal Investigator of the Mars Observer Camera to Thomas E. Thorpe, Mars Observer Project Science Manager, June 15, 1990.

subcomponent prices paid by the Project Office.[29] For the experiments, the differences in these figures provide a broad indication of the total margin allocations transferred from the Project Office. Further, much of the difference between initial and final spacecraft prices is attributable to the incremental, experiment driven unilateral modifications to the spacecraft contract -- this too is an allocation of margins to the experiment by the Project Office. One caveat should be stated -- physical resource margin increases (e.g., mass) for different experiments affected the spacecraft design differently. Therefore the portion of the spacecraft price increases attributable to experiment margin allocations cannot be apportioned among the experiments directly by their margin allocations.[30] Spacecraft unilateral modifications were often issued by the Project Office to accommodate numerous experiment margin allocations and there is no dependable accounting approach available to deduce the spacecraft price increases attributable to each experiment.

Figure 2.4: Subcomponent Initial Estimated Prices vs Final Prices



Figures 2.3 and 2.4 may well overstate the disparity between expected prices and actual prices. A very strong case can be made supporting the contention that NASA did

[29]As mentioned previously, the final price of the imaging experiment includes a number of upgrades and additions specifically requested, and partially funded, by NASA which in total account for perhaps $5M of the $17.5M difference between initial estimated cost and final price.

[30]For example, mass margin allocations to the gamma ray spectrometry experiment had a vastly greater impact on the spacecraft center of mass than any other experiment due to this experiment's deployment on a long boom away from the body of the spacecraft.

not believe in, or intend to constrain the Project Office to, the initial \$250 million total budget for the mission at the time when the bilateral monopolies were established.[31] All the same, the fundamental acts of re-contracting for six of the eight major subcomponents suggest price escalation beyond the means and expectations of either the Project Office or NASA. Further, the acts of re-contracting can be explained as reactions to the inadequate acknowledgment of moral hazard driven inefficiencies in the initial subcontracts. The analysis supporting this contention is provided as Chapter 6 and benefits in exposition and credence from the intervening analytical treatments of Chapters 3, 4, and 5.

[31]See Charles Polk, 1990.

Chapter 3: Vertically Integrated Subcomponent Production

3.0 Introduction to the Analytical Treatment

The analysis provided in Chapters 3, 4, and 5, models R&D as a two step process, influenced by a correlation between the probabilistic nature of innovation and the self-interested parties engaged in innovation. In Chapter 3 we introduce the basic production process removed from any agency complications. In Chapter 4 we analyze the same production process with a profit motivated agent and each of two types of principal; one contracting for an immediately marketable final good, the other for a single subcomponent to a final good composed of numerous subcomponents. Comparisons of our approach to that of the existing production organization literature are most appropriately made in Chapter 4 due to the commonalty of profit motivated agency. In Chapter 5 we introduce a different type of agent, one motivated by the capability of his subcomponent. The two types of subcomponent agency that are modeled in Chapters 4 and 5 correspond to the profit seeking and performance seeking agents described in the Mars Observer case study of Chapter 2.

We define R&D as follows: Research involves the effort to enhance the technological inputs to a particular subcomponent while Development incorporates the outcome of Research into actual production. R&D can be modeled as an iterative Research process leading to the version of a prototype considered optimal which is then Developed.[32] Alternatively, a single Research endeavor may be undertaken with the intent of innovating a subcomponent to a many component final good. By this alternate model, the innovation will be Developed into the necessary subcomponent if it will result in value superior to available substitutes as assessed by the entity responsible for organizing final good production. The latter process does not preclude further R&D on the same subcomponent or any other, it simply reflects the incremental technological

[32] Guofu Tan, "Incentive Procurement Contracts with Costly R&D," *Caltech Social Science Working Paper 702*, June 1989.

evolution of a complex production process. As we wish to model subcomponent production, we adopt the more incremental definition of R&D.

A non-iterative, two step view of subcomponent R&D has advantages in the scope over which it may apply. By considering a production process organized by one Principal, but which integrates numerous distinct subcomponents, the incremental incorporation of technological advancement is explicitly considered. The Principal's overall R&D problem begins with the allotment of 'heritage'; namely, which subcomponents should rely on existing technology. This results in a clear division of subcomponents into those which will be bought 'off-the-shelf' from vendors and those which will undergo R&D. Those subcomponents targeted for R&D must then pass through the 'Make-or-Buy' procurement decision; namely, a decision over whether the R&D process should be managed directly by the Principal or contracted to another entity. The 'Make-or-Buy' decision will have much to do with the available contracting regimes and the various impacts of moral hazard.

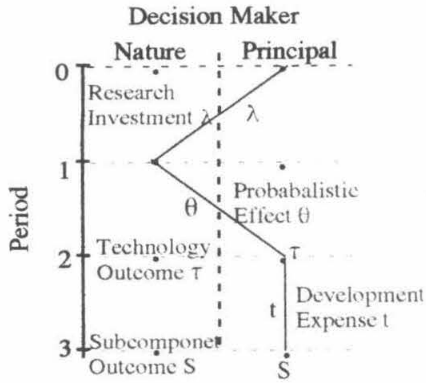
3.1 The Simple Case of Vertical Integration

Before considering various contracting regimes in Chapters 4 and 5, we begin with an analysis that includes the production processes and Principal which will be common throughout this work; however, our analysis will be uncomplicated by agency issues. Our introductory approach is meant to establish the basic qualities of the processes and the intent of the Principal so that the effects of agency on R&D subcomponent production may be distinguished later.

Research is the initial process of innovation and its outcome, technology, is an interim goal of production, the qualities of which will affect the worth of proceeding with the Development of an innovated subcomponent. If the level of technology produced from the Research process can be used to Develop a subcomponent in a manner superior in price and/or capability to existing subcomponents, then Development will proceed, else innovation will be suspended and an "off-the-shelf" subcomponent will be used. Implicit in this description of Research and the decision process over the employment of its output, technology, is the probabilistic nature of technological innovation.

A common nomenclature and clearly defined decision timing pattern are adopted to facilitate analytical treatment: Figure 3.1 provides a simple four period model of vertically integrated R&D. Each period represents an outcome, with the paths between periods representing decisions that affect the next outcome. Under the assumption that the Principal is cognizant of the nature of the whole process it is appropriate to describe Figure 3.1 from the period 3 outcome backward (the nomenclature defined here will be standard throughout the thesis).

Figure 3.1: Decision Flow for Vertically Integrated Production



Given an arbitrary production budget of B, the Principal has residual funds of Π = B-λ-t for production of other subcomponents

The period 3 outcome is a subcomponent with capability S where S is a function of the technology outcome of Research, τ, and the amount of Development funding, t. Final production is assumed to proceed after period 3 with S being combined with other subcomponents purchased using funds, Π, residual to the R&D effort. The Principal values subcomponent production of S relative to all of the subcomponents comprising the final good; therefore, the Principal's utility function is modeled as $U[S(\tau, t), \Pi]$.

The period 2 outcome is the technology, τ, developed from the Research process. τ is positively dependent upon the Principal's past Research investment decision, λ, and a probabilistic element, θ, drawn from a publicly known random distribution $F(\theta)$ with density $f(\theta)$. The minimum possible technology outcome is fixed by the pre-Research technology which will be referred to as the "off-the-shelf" level of technology and denoted as τ_0. Upon observing τ, the Principal decides what level of Development funding, $t(\tau)$, to invest in the production of S.

The period 1 outcome is simply that a Research effort funded by an investment λ is underway. Nature will make the probabilistic decision θ that will critically affect the Research process.

The Period 0 outcome is that the Principal, having conducted a heritage decision process over all subcomponents to a final good, has concluded *that the* subcomponent, S, should undergo R&D. The Principal, knowing the nature of the coming R&D process, decides on a Research investment of λ.

The following functional characteristics specify the nature of the R&D process described above and illustrated in Figure 3.1:

Outcome of Research is technology = $\tau(\lambda, \theta)$

$\tau(\lambda, \theta)$ is concave in both arguments $\tau_i > 0$, $\tau_{ii} < 0$

$\tau(0, \theta) = \tau_o$ [off-the-shelf] for all θ

$\tau(\lambda, \theta) \geq \tau_o$ for all $\lambda \geq 0$ [revert to τ_o if θ outcome is 'bad']

$\tau(\lambda, \theta) \leq \tau_{max}$ for all $\lambda > 0$ [support of $f(\theta)$ is independent of λ]

Outcome of Development is the subcomponent $S(\tau, t(\tau))$,

S is concave in both arguments [$S_i > 0$, $S_{ii} < 0$], and $S_{\tau t} > 0$

$t(\tau)$ is Development funding

$S(\tau, 0) = 0$ for all τ.

Principal's Utility = $U(S, \Pi)$, U is concave in both arguments [$U_i > 0$, $U_{ii} < 0$]

S represents a subcomponent undergoing R&D

Π is funding for 'off-the-shelf' sub-components

The budget for production of the final good is B [arbitrary for our purposes]

Assumption 3.1: The optimal Research investment is positive, $\lambda^* > 0$. The production process motivates this assumption in that if $\lambda^* = 0$, then the Principal is essentially deciding that all subcomponents should be 'heritage' subcomponents; i.e., no R&D should be done. $\lambda^* = 0$ would thus contradict the assumption that the initial condition at period 0 is that the decision has already been made to innovate the subcomponent S.

Solving backwards -- We first solve for Second Period Production Funding, $t[\tau(\lambda,\theta)]$:

$$\pounds_2 = U\left[S(\tau, t), B - \lambda - t\right] + \gamma t \qquad \begin{array}{l} \gamma = 0 \text{ if } t > 0 \\ \gamma > 0 \text{ if } t = 0 \end{array} \tag{3.1}$$

$$\frac{\partial \pounds_2}{\partial t}: S_t U_S - U_\pi + \gamma = 0 \quad \forall \left(\lambda^*, \theta\right) \tag{3.2}$$

We know that the solution t* to (3.2) will be a maximum if $\frac{\partial^2 £_2}{\partial t^2} < 0$

$$\frac{\partial^2 £_2}{\partial t^2} = S_{tt}U_S + S_t^2 U_{SS} - 2S_t U_{S\pi} + U_{\pi\pi} \qquad 3.3$$

Note that given the concavity of U and S, (3.3) will most certainly be less than zero if $U_{S\pi} \geq 0$. The principal's utility is relative to the outcome of a final good production process which, by construction, is positively and jointly influenced by several subcomponents that are assembled to produce the final good. S is one such subcomponent and Π is a proxy for the other subcomponents as it represents the ability to procure them. $U_{S\pi} \geq 0$ is a mathematical representation of the positively and jointly valued nature of the various subcomponents in final good production; namely, the marginal value of increasing the capability of one subcomponent is increasing in the capability of all other subcomponents. Henceforth, this property will be referred to as 'balance', in the sense that the Principal wishes to balance the constituent worth of all of the subcomponents relative to the final good.

Assumption 3.2: $U_{S\pi} \geq 0$.

Some comparative statics for the second period, Development funding decision, t*, illuminate the nature of the process and the effect of the research outcome, $\tau(\lambda, \theta)$ on the optimal funding decision:

$$\frac{\partial t^*}{\partial \theta} = \frac{-\tau_\theta(S_{\tau t}U_S + S_\tau S_t U_{SS} - S_\tau U_{S\pi}) - \gamma_\theta(\lambda, \theta)}{SOC_2} = -\frac{\partial \pi^*}{\partial \theta} \qquad 3.4$$

$$\frac{\partial t^*}{\partial \lambda^*} = \frac{-\tau_\lambda(S_{\tau t}U_S + S_\tau S_t U_{SS} - S_\tau U_{S\pi}) + S_t U_{S\pi} - U_{\pi\pi} - \gamma_\lambda(\lambda, \theta)}{SOC_2}. \qquad 3.5$$

This implies that

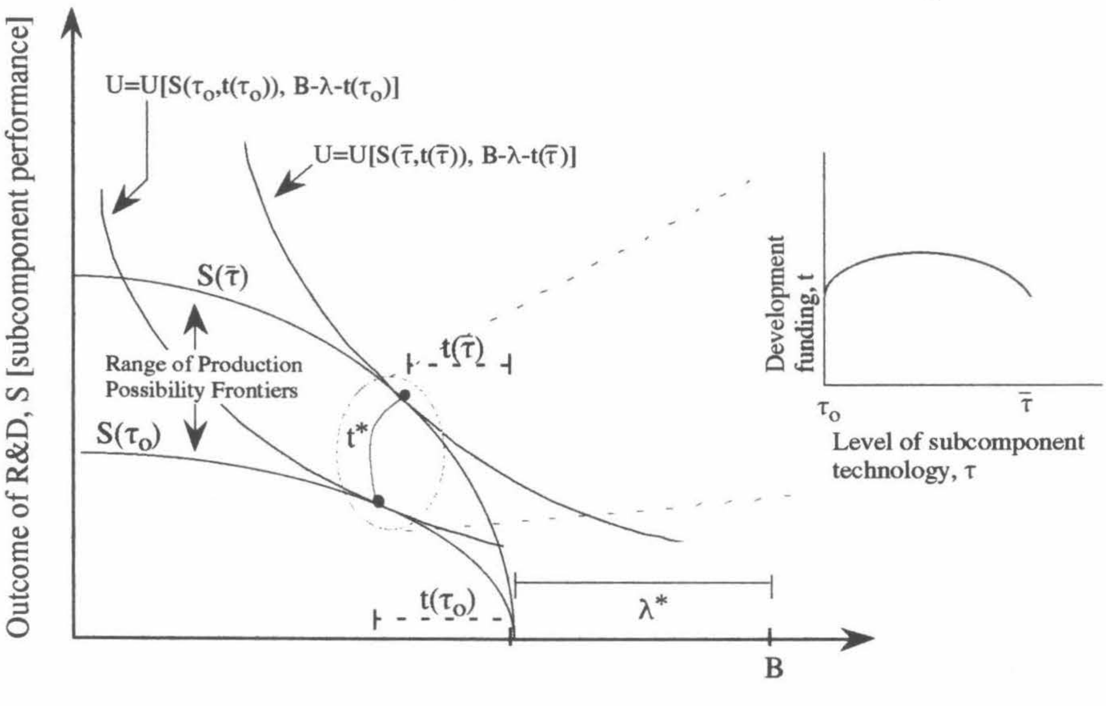
$$\text{For } \left(\lambda^*, \theta\right) \ni -S_\tau S_t U_{SS} + S_\tau U_{S\pi} > S_{\tau t}U_S,\ \frac{\partial t^*}{\partial \lambda^*} \leq \frac{\partial t^*}{\partial \theta} \leq 0, \qquad 3.6$$

While

$$\text{For}\left(\lambda^*,\theta\right) \ni -S_\tau S_t U_{SS} + S_\tau U_{S\pi} < S_\pi U_S,\ \frac{\partial t^*}{\partial\theta} \geq 0 \text{ and } \frac{\partial t^*}{\partial\theta} \geq \frac{\partial t^*}{\partial\lambda^*}. \qquad 3.7$$

Note that for any level of Research funding (λ), Development funding (t) may be decreasing in relation to the outcome of the Research [$\tau(\lambda, \theta)$]. Development funding that decreases in the outcome of a beneficial learning phase for one subcomponent is intuitively reasonable for multi-component production, because of the jointly valued worth of each subcomponent in the final product. This is implicit in the assumption that U is concave and not necessarily separable in S and π and is strengthened be Assumption 3.2. Figure 3.2 illustrates the principal's utility space relative to Development funding. A potential $t^*(\tau)$ funding schedule is shown which is both increasing and decreasing in τ.

Figure 3.2: Principal's Utility Space with Sample Indifference Curves, Production Possibilities Frontiers, Research and Development Funding



Funds remaining for purchase of other subcomponents, Π

Next we solve for First Period Research Funding, λ:

$$£_0 = \int U\Big[S\big(\tau(\lambda, \theta), t^*(\lambda, \theta)\big), B - \lambda - t^*(\lambda, \theta)\Big]f(\theta)d\theta \qquad 3.8$$

$$\frac{\partial £_0}{\partial \lambda} : \int \Big[U_S\big[\tau_\lambda S_\tau + t^*_\lambda S_t\big] - U_\pi\big[1 + t^*_\lambda\big]\Big]f(\theta)d\theta = 0 \qquad 3.9$$

$$\frac{\partial £_0}{\partial \lambda} : \int \Big[\tau_\lambda S_\tau U_S - U_\pi + t^*_\lambda\big[S_t U_S - U_\pi\big]\Big]f(\theta)d\theta = 0 \qquad 3.10$$

From (3.2): $S_t U_S - U_\pi = \gamma^*(\lambda, \theta) \ \forall \theta$

$$\frac{\partial £_0}{\partial \lambda} : \int \Big[\tau_\lambda S_\tau U_S - U_\pi - \gamma^*(\lambda, \theta) t^*_\lambda\Big]f(\theta)d\theta = 0 \qquad 3.11$$

From the Kuhn-Tucker conditions: $\gamma^*(\lambda, \theta)t^*_\lambda = 0$; therefore

$$\frac{\partial £_0}{\partial \lambda} : \int \Big[\tau_\lambda S_\tau U_S - U_\pi\Big]f(\theta)d\theta = 0. \qquad 3.12$$

From (3.12) we determine the second derivative of (3.8) with respect to λ

$$\frac{\partial^2 £_0}{\partial \lambda^2} = \int \Big[\tau_{\lambda\lambda} S_\tau U_S + \tau_\lambda^2 S_{\tau\tau} U_S + \big(\tau_\lambda S_\tau\big)^2 U_{SS} - \tau_\lambda S_\tau U_{S\pi} + U_{\pi\pi}\Big]f(\theta)d\theta \qquad 3.13$$

Note that (3.13) is always ≤ 0; thus, the solution, λ*, to (3.9) is a maximum.

Theorem 1.1: The solution (λ*, t*) to the R&D production model without agency concerns is the unique optimum.

Proof: Immediate from Assumptions 3.1 & 3.2, the second order conditions (3.3) & (3.13), and the linearity of the constraint in (3.1). **QED**

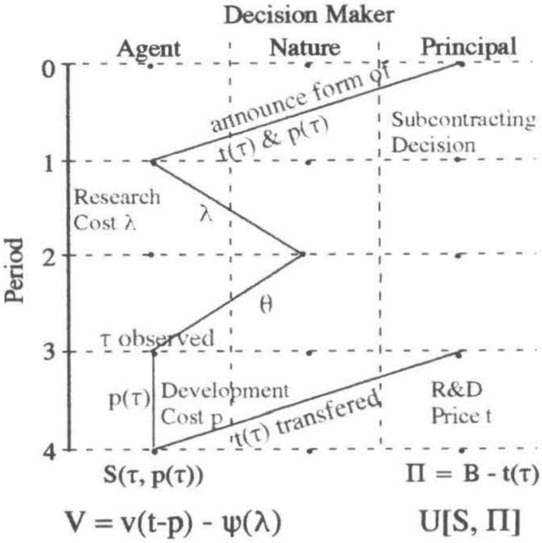
In the absence of agency concerns, R&D subcomponent production organization is a straight forward multi-period dynamic programming process with decisions contingent on an observable Research outcome. The implicit value from balancing the performance contributed from the R&D subcomponent with the performance obtainable from other purchased subcomponents results in the explicit fact that Development funding may be negatively related to the success of Research. Such a negative relationship is analogous to the margin contacts described in Chapter 2 for the experiment subcomponents on Mars Observer.

Chapter 4: The Effects of Moral Hazard on R&D Procurement from a Profit Seeking Agent

4.0 Profit Seeking Agent within a Subcomponent R&D Model

In Chapter 4 we introduce an agent into the R&D subcomponent production process. When contracting with an agent, the process is physically the same as has been illustrated in Figure 3.1 of Chapter 3. With agency, the organization of the R&D process for subcomponent S will vary depending on the type of agency and the information environment. Profit seeking agency is illustrated in Figure 4.1 with the principal facing the single information asymmetry that the outcome of Research, τ, is observed by both the principal and the agent, but the inputs to Research, λ and θ, are observed only by the agent.

Figure 4.1: Decision Flow if Contracting with a Profit Seeking Agent



Research funding, λ, is chosen by the agent relative to the same publicly known probabilistic quality of the Research process for this subcomponent that pertained in Chapter 3 (modeled as the random variable θ with density $f(\theta)$). Upon observing the outcome of Research, τ, the agent chooses a level of Development funding, $p(\tau)$, that is either directly observed by the principal or is effectively observed due to the principal's assumed knowledge of the production function for S and the observation of τ. Upon delivery of the subcomponent, the agent receives a payment based on a compensation function $t(\tau)$ that was determined when the principal contracted the agent at the start of the R&D process. As modeled, the flow of funds from principal to agent represents a pure reimbursement contract. In practice, the flow of funds might well be some mix of prepayment and reimbursement.[33] As our analysis is based on characterizing an optimal incentive compatible direct revelation (ICDR) contract, the Revelation Principle will assure that the optimal contract used in practice, regardless of its flow of funds, will correspond to the optimal ICDR contract based on the flow of funds illustrated.[34]

If an optimal ICDR contracting arrangement is possible, then the Research funding, λ, chosen by the agent will be truthfully revealed to the principal; thus, the agent can be directly compensated for λ, leaving the agent's profit (net revenue) as $(t - p)$. The agent, however, may have limited access to agent-specific Research assets such that committing 'λ-worth' of these assets represents an opportunity cost beyond simple transferable monetary expense; therefore, the function $\psi(\lambda)$ is included in the agent's utility function, V, to account for this opportunity cost.

Implicit in the structure of the process illustrated in Figure 4.1 is that the principal can enforce the outcome, S, of the subcomponent R&D production process. This means that the level of S delivered must be greater than or equal to the level that would result from the observed technology, τ, and the observable Development funding $p(\tau)$, else $t(\tau)$ will be withheld from the agent. If the principal cannot credibly withhold $t(\tau)$, or in some other manner punish the agent, then the contract cannot be enforced. If the outcome of a proposed ICDR contract with a profit seeking agent cannot be enforced, then the proposed contract must be rejected as the agent's interests could not be credibly aligned with the principal's interests.

Before proceeding with the analysis, we characterize some ICDR analogs to a number of actual contracts so that the applicability of the results from Chapters 4 and 5 will be more apparent. Figure 4.2 illustrates three types of contracts pertinent to actual

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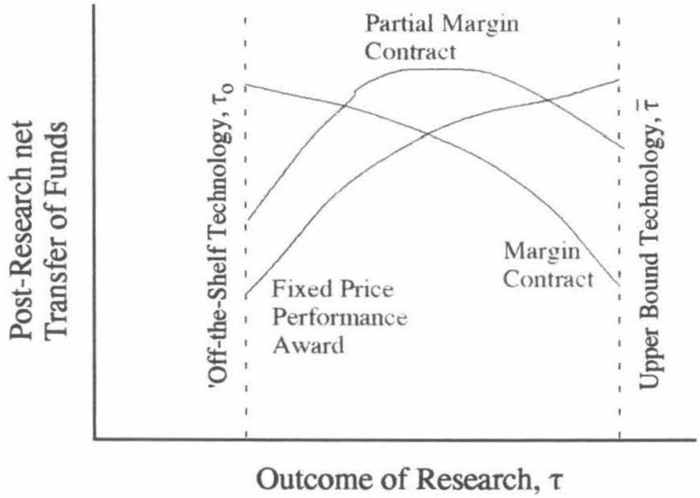
[33]In the extreme, a contract with a warranty can be thought of as an over-payment contract where, depending on the performance of the item purchased, the agent may be obliged to return some portion of the prepayment.

[34]For a basic treatment of the Revelation Principle see, Roger B. Myerson, "Incentive Compatibility and the Bargaining Problem," *Econometrica*, vol. 47, no. 1, January 1979, pages 61-73. The terminology and use of the Revelation Principle employed in this thesis can be more directly referenced in, Roger B. Myerson and Mark A. Satterthwaite, "Efficient Mechanisms for Bilateral Trading," *Journal of Economic Theory*, vol. 29, 1983, pages 267-268.

contracting that may result from the theoretical analyses that follow. The fixed price/performance award (FPPA) contract is a straight forward reward contract. The pure margin contact is somewhat analogous to an insurance contract, providing greater funding for Research Outcomes increasingly affected by bad luck. The partial margin contract is any mix of the FPPA and pure margin contract. As shown in Chapter 3, without agency all three of these contracts represent possible optimal post-Research expenditures. In Chapter 4 we will show that the pure margin contract is not a possible optimal ICDR contract for profit seeking agency, though the FPPA and partial margin contracts are. In Chapter 5 we will show that all three are possible optimal ICDR contracts for performance seeking agency.

Figure 4.2: Potential ICDR Analogs of Several Actual R&D Contract Forms



4.1 Relationship to Past Research

A production process captured by the first three periods of Figure 4.1 and simplified with a profit motivated principal contracting for a complete and marketable good S [e.g.; U = U(S - \$)] is essentially the simple moral hazard process studied by Ross [1973], Holmström [1979] and others.[35] To establish a connection with the existing body

[35] These authors have relied on the Revelation Principal to validate ICDR approaches that employ analysis of first order optimization conditions, as will be done throughout this thesis. Although the

of optimal contracting literature, the standard moral hazard problem is examined using the nomenclature employed throughout this thesis:

> The utility functions are simplified for the single component, single stage case: Principal's Utility; $U = U[S - t(\tau)]$: Agent's Utility; $V = v(t) - \psi(\lambda)$ with U and v concave ($U' > 0$, $U'' \leq 0$: $v' > 0$, $v'' \leq 0$), and ψ convex ($\psi' > 0$, $\psi'' \geq 0$).
>
> Given one-stage production, there is no interim production output, τ; thus, the influence of the probabilistic element, θ, is direct on the production of S.
>
> To ease mathematical analysis we take the conventional approach of suppressing θ by viewing S as a random variable with distribution $F(S, \lambda)$ and finite support $[S_o, \bar{S}]$. Given a distribution of θ, $F(S, \lambda)$ is the distribution induced on $\tilde{S}$ via the relationship $\tilde{S} = S(\lambda, \theta)$. Further, assume that F is convex in λ; i.e., $F_\lambda < 0$, $F_{\lambda\lambda} > 0$.

The goal of this introductory analysis, and of all the analyses to follow, is to characterize an optimal incentive compatible contracting arrangement between principal and agent. Analysis proceeds in a standard fashion by defining the agent's optimization problem and then incorporating conditions that characterize the agent's optimum as constraints on the principal's choices of the contracting arrangement.[36] The agency constrained principal's problem can be solved with respect to the decision variables and functionals of both the principal and agent -- the solutions to the first order conditions (if a maximum) will be an optimal ICDR contract form the principal's point of view.

Agent's Problem:

$$\text{ICC:} \quad \frac{d}{d\lambda}\left\{\int [v(t) - \psi(\lambda)] f dS\right\} = 0 \Rightarrow \int v f_\lambda dS - \psi' = 0 \qquad 4.1$$

---

functional forms chosen and the questions of interest have varied, each of these authors have been able to characterize the optimal contract as positively monotonic in the outcome of the complete good that the agent was contracted to produce (e.g., an FPPA contract). Positive monotonicity is intuitively reasonable as both principal and agent are unambiguously made better off by increasing output in models with transferable utility.

[36] All analyses are conducted under the assumption that the principal is a monopsonist who may retain the agent's services subject to a known reservation wage.

Namely, the Agent wishes to balance the opportunity cost of expending λ against the expected utility of profiting from the outcome of production, S.

Principal's Agency Constrained Problem:

$$J = \int UfdS + \gamma\int \left[v(t) - \psi(\lambda)\right]fdS + \mu\left[\int vf_{\lambda}dS - \psi'\right] + \delta\lambda \tag{4.2}$$

A necessary condition for optimum Research investment, λ, is:

$$\frac{dJ}{d\lambda}: \int Uf_{\lambda}dS + \mu\left[\int vf_{\lambda\lambda}dS - \psi''\right] = -\delta \tag{4.3}$$

Integrating by parts, (4.3) becomes

$$UF_{\lambda}\Big|_a^b - \int_a^b F_{\lambda}U'[1 - t']dS + \mu\left[vF_{\lambda\lambda}\Big|_a^b - \int_a^b F_{\lambda\lambda}t'v'dS + \psi''\right] = -\delta \tag{4.4}$$

The nature of the distribution function, $F(\theta, \lambda)$, allows for two useful simplifications:

$$F(a, \lambda) = 0 \; \forall \; S, \; F(b, \lambda) = 1 \; \forall \; S; \; \therefore \; UF_{\lambda}\Big|_a^b = vF_{\lambda\lambda}\Big|_a^b = 0 \;\; \forall S$$

Therefore, 4.4 can be rewritten as

$$-\int F_{\lambda}U'[1 - t']dS - \mu\left[\int F_{\lambda\lambda}t'v'dS + \psi''\right] = -\delta \tag{4.5}$$

The necessary condition for the optimal transfer, t(S), is:

$$\frac{dJ}{dt}: \; -U' + \gamma v'f + \mu v'f_{\lambda} = 0 \;\; \forall S$$

$$\frac{U'}{v'} = \gamma + \mu\frac{f_{\lambda}}{f} \;\; \forall S \tag{4.6}$$

The optimal transfer can be characterized by differentiating both sides of (4.6) with respect to S:

$$t' = \frac{v'U'' - \mu v'^2 \, d/dS\left(f_{\lambda}/f\right)}{v'U'' + v''U'} \;\; \forall \, S \tag{4.7}$$

Assumption 4.1: $\frac{\partial}{\partial S}\left(\frac{f_{\lambda}}{f}\right) \geq 0$ {Monotone Likelihood Ratio Property , Standard}

Given the concavity of U and v, Assumption 4.1, and noting that $\mu > 0$ [due to Hölmstrom, 1979], equation (4.7) is signable as greater than or equal to zero over all S. Referring to Figure 4.2, equation (4.7) therefore characterizes a fixed price/performance award contract.

Theorem 4.1: Given Assumption 3.1, the solutions (λ^*, $t^*(S)$) to the first order conditions of the Principal's Problem [(4.3) and (4.6)] are the unique optimum for the case of complete production with a profit-seeking agent and one-stage production.

Proof: Equation (4.7) satisfies an interior maximum sufficient condition for the agency constraint of (4.5) [the Agent's Problem]; this condition is the standard positive monotonicity result:

$$t' \geq 0 \ \forall S^{37} \qquad 4.8$$

A corresponding sufficient condition for an interior maximum to the Principal's Problem (i.e., $\delta = 0$) is $t' \leq 1$ for all S [the condition is apparent from (4.5)]. This sufficient condition does not necessarily follow from equation (4.7); however, if we accept the motivating rationale of Assumption 3.1 ($\lambda^* > 0$), then showing sufficiency for the principal is not necessary, as the principal would not have chosen subcomponent S to undergo R&D if, in expectation, he knew that choosing no R&D would result in at least as satisfactory an outcome.[38] Accepting Assumption 3.1 also eliminates concern over the solutions to (4.5) and (4.6) being a local minimum as such a solution clearly would not have led the principal to choose the subcomponent S for R&D. Finally, the LeGendre condition is satisfied by (4.2). **QED**

Corollary 4.1: Theorem 4.1 does not require Assumption 3.1 if the following relationship between the agent's relative risk aversion and the influence of moral hazard on the production organization problem holds:

$$-\frac{v''}{v'} \geq \frac{\mu v' \frac{d}{dS}\left(\frac{f_\lambda}{f}\right)}{U'} \quad \forall S \qquad 4.9$$

which can be restated conceptually as

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[37]The sufficient condition represented by (4.8) also has the interpretation that for any given investment by the agent, λ, each differential increase in S results in more profit for the agent.

[38]From (4.7) it is evident that without asymmetric information (i.e., $\mu = 0$), $t' \leq 1$ is satisfied.

$$\begin{bmatrix} \text{The Agent's} \\ \text{Relative Risk} \\ \text{Aversion} \end{bmatrix} \text{must be} \geq \begin{bmatrix} \dfrac{\text{Agent's Marginal Value of Revenue}}{\text{Principal's Marginal Value of Revenue}} \end{bmatrix} * \begin{bmatrix} \text{Agency Effect} \\ \text{of} \\ \text{Moral Hazard} \end{bmatrix}, \begin{pmatrix} \text{for all} \\ \text{performance} \\ \text{outcomes} \end{pmatrix}.$$

Proof: As stated in the proof of Theorem 4.1, a sufficient condition for the principal's maximization is $t' \geq 1$ for all S. Corollary 4.1 may thus be proven immediately by setting the left side of (4.7) less than or equal to 1. **QED**

Corollary 4.2: Equation (4.9) is an overly strong sufficient condition for proving Theorem 4.1.

Proof: By differentiating (4.5) w.r.t. λ, sufficiency only requires that

$$-\int F_{\lambda\lambda} U'[1 - t']dS < 0, \text{ yet } 4.9 \Rightarrow F_{\lambda\lambda} U'[1 - t'] < 0 \ \forall \ S. \ \textbf{QED}$$

The classic optimum contracting problem under a moral hazard agency condition ends here. The application modeled, the production function, the utility functions, and the probabilistic environment may vary, but the following two qualities of production organization remain the same in the classic treatments: one stage production, and procurement of a single component directly valued by the principal. The remainder of Chapter 4 will examine the effects of altering these two qualities with emphasis on modeling the incremental subcomponent R&D production that appears relevant to real-world final good production.

4.2 One Stage R&D Subcomponent Production

The full R&D version of production organization diverges from the standard in two respects:

(i) Subcomponent rather than complete production is modeled -- The outcome of R&D, S, is not directly valued, rather it is one of a number of components constituting a valued final product [$U = U(S, \Pi)$].

(ii) A two-stage R&D process is modeled -- The outcome of Research becomes an input to Development.

It is appropriate to examine the effects of (i) and (ii) separately before combining them into a full analysis. In section 4.2, the most immediate departure from section 4.1 is made; namely, one-stage subcomponent production is analyzed. The nomenclature and functional assumptions remain unchanged from section 4.1 with the exceptions that U = U(S, Π), U is concave ($U_i > 0$, $U_{ii} \leq 0$), and Assumption 3.2 holds ($U_{S\pi} \geq 0$).

Agent's Problem:

$$\text{ICC: } \frac{d}{d\lambda}\left\{\int \left[v(t) - \psi(\lambda)\right] f dS\right\} = 0 \Rightarrow \int v f_\lambda dS - \psi' = 0 \qquad 4.10$$

Principal's Agency Constrained Problem:

$$J = \int U f dS + \gamma \int \left[v(t) - \psi(\lambda)\right] f dS + \mu\left[\int v f_\lambda dS - \psi'\right] + \delta\lambda \qquad 4.11$$

Necessary condition for an optimum in λ:

$$\frac{dJ}{d\lambda}: \int U f_\lambda dS + \mu\left[\int v f_{\lambda\lambda} dS - \psi''\right] = -\delta \qquad 4.12$$

Integrating by parts, (4.12) becomes

$$-\int F_\lambda\left[U_S - t' U_\pi\right] dS - \mu\left[\int F_{\lambda\lambda} t' v' dS + \psi''\right] = -\delta \qquad 4.13$$

Necessary condition for an optimum in t(S):

$$\frac{dJ}{dt}: -U_\pi + \gamma v' f + \mu v' f_\lambda = 0 \ \forall S$$

$$\frac{U_\pi}{v'} = \gamma + \mu \frac{f_\lambda}{f} \ \forall S \qquad 4.14$$

The optimal transfer can be characterized by differentiating both sides of (4.14) with respect to S:

$$t' = \frac{v' U_{S\pi} - \mu v'^2 \, d/dS\left(f_\lambda / f\right)}{v' U_{\pi\pi} + v'' U_\pi} \qquad 4.15$$

The agent has not changed between the standard moral hazard problem (Section 4.1) and this subcomponent case; therefore, positive monotonicity remains a sufficient condition for the agent's maximization problem. However, unlike the contract characterized by equation (4.7) for a principal organizing complete production, (4.15) is not signable; it may be increasing or decreasing over all, part, or none of the range of S. With reference to Figure 4.2, the contract characterized by equation (4.15) may be any variation of the contracts shown, not just the FPPA contract yielded under complete production (section 4.1). This is a direct result of the positive tradeoff in the principal's utility function represented by $U_{S\pi} \geq 0$ and is analogous to the results of the no agency analysis of Chapter 3. Further, in direct contrast to complete production, under full information ($\mu = 0$), $t' \leq 0$ for all τ. This is a crisp indication of the fundamentally different valuation faced by a principal organizing production at the subcomponent rather than the final good level.

The principal has, however, changed. A sufficient condition for the principal to organize an R&D effort for the subcomponent S ($\lambda^* > 0$), assuming that the solution to the Agent's problem was optimal, is that the slope of the transfer must be less than the ratio of the marginal valuations [immediate from (4.13]:

$$t' \leq \frac{U_S}{U_\pi} \quad \forall S \qquad \text{[analogous to } t' \leq 1 \text{ in Section 4.1].} \tag{4.16}$$

This can be rewritten in terms of the Agent's relative risk aversion:

$$-\frac{v''}{v'} \geq \frac{U_S U_{\pi\pi} + U_\pi\left[\mu v' \frac{d}{dS}\left(\frac{f_\lambda}{f}\right) - U_{S\pi}\right]}{U_S U_\pi} \quad \forall S \tag{4.17}$$

It should be clear that the sufficient condition represented by (4.17) is not assured. Therefore, the solutions to first order conditions of the Principal's Problem need not represent optimal incentive production organizations; in other words, no Theorem analogous to Theorem 4.1 can be proven for section 4.2.

The nature of possible solutions to the necessary conditions [(4.13) & (4.14)] can be exhaustively characterized by examining cases within three categories: Interior maximum, no R&D corner solution [$\lambda^* = 0$], and a minimum. However, a fundamental assumption of the production processes examined in this research is that the decision to invest in the innovation of a subcomponent is made relative to an existing set of subcomponent choices. The decision to contract an agent for the R&D of a subcomponent is thus made with the knowledge that

$$\int U[S, B - t(S)]f dS > U[S_o, B - P_{S_o}]$$

where P_{S_o} = price of S_o and S_o is the known existing subcomponent which the Principal has decided to have innovated. This is the justification for Assumption 3.1 ($\lambda^* > 0$), and is also the justification for our not bothering to characterize solutions to the Principal's Problem that represent no R&D corner solutions or a minimum. The possible solutions representing interior maxima are mathematically described below and illustrated in Figures 4.3 through 4.6:

Interior maximum

Case A: $t' \leq \frac{U_S}{U_\pi} \ \forall S$ and $\psi'' > -\int F_{\lambda\lambda} t'v' dS$: the contract explicitly satisfies the overly strong sufficient condition that the principal is better off for each differential increase in S, but only satisfies the weakest condition for the agent.

Case B: $0 \leq t' \leq \frac{U_S}{U_\pi} \ \forall S$: the contract explicitly satisfies the overly strong sufficient conditions that both Principal and Agent are better off for each differential increase in S.

Case C: $t' \geq 0 \ \forall S$, $-\int F_\lambda [U_S - t'U_\pi] dS \geq 0$, and $-\int F_{\lambda\lambda} [U_S - t'U_\pi] dS \leq 0$: the contract explicitly satisfies the overly strong sufficient condition that the agent is better off for each differential increase in S, but only satisfies the weakest conditions for the principal.

Case D: $t' \geq 0$ & $t' \leq \dfrac{U_S}{U_\pi}$ for enough S such that the sufficient conditions hold.

Caveat: Case A allows for a complete margin contract, t' ≤ 0 for all S. However, with the reasonable assumption that the cost of innovating S, λ, is greater than the 'Off-the-Shelf' price of S_o, then t' ≤ 0 for all S is not an interior maximum as the Agent would perform no Research, buy S_o 'Off-the-Shelf', and pocket the difference. Similar reasoning precludes the fixed price contract (t' = 0 for all S) from consideration as an optimal contract.

Figure 4.3: Case A
Partial Margin Contact, Principal Bias

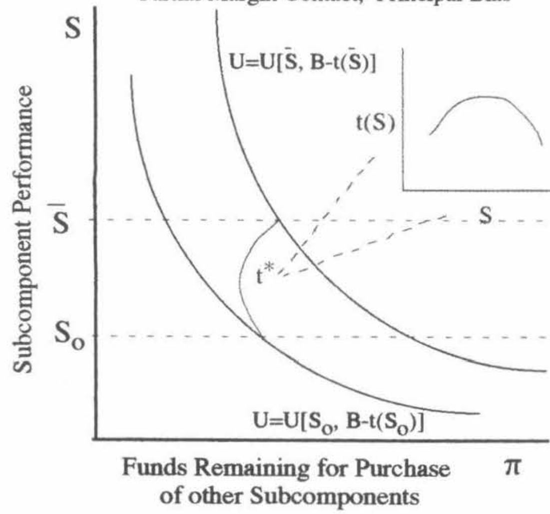


Figure 4.4: Case B
Fixed Price/Performance Award, no Bias

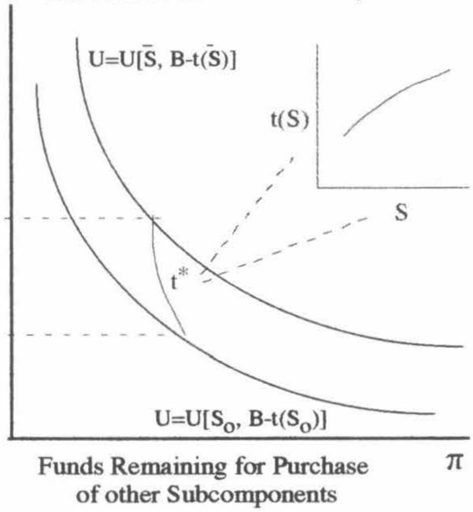


Figure 4.5: Case C
Fixed Price/Performance Award, Agent Bias

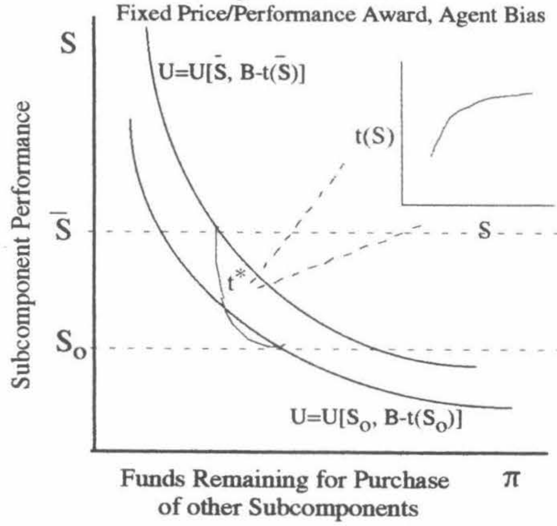
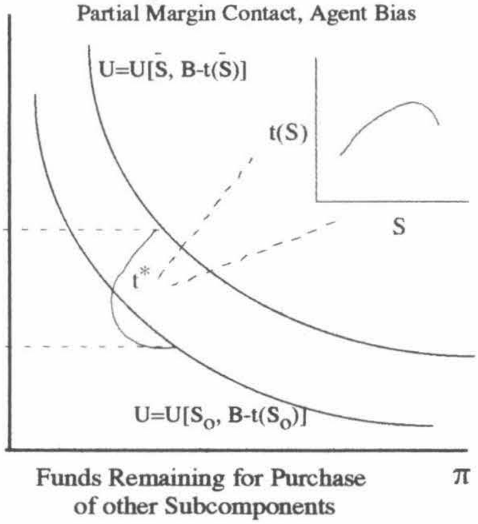


Figure 4.6: Case D
Partial Margin Contact, Agent Bias



Cases B and C have the characteristics of the optimal FPPA contract assured by Theorem 4.1 in section 4.1: $t' \geq 0$ for all S. The additional complication of a subcomponent production process has rendered Cases B and C to be two of four possible optimal production organizations within a production process that, without assuming an interior solution, need not have an interior optimum.

4.3 Standard Two Stage R&D Production

The two-stage, production process shown in Figure 4.1, but simplified with U = U[S - t], is markedly similar to the R&D model of Guofu Tan [June 1989].[39] Tan models both single and multiple agent cases. His single agent case is the one of interest here. His model's fundamental difference from ours is that the outcome of Research (τ) along with the inputs to research (λ, θ) are not observable, only the final output is observable. Thus, the root moral hazard problem is augmented by an interim adverse selection problem.[40] The two models diverge further in the functional restrictions that Tan imposes: Agent and Principal are risk neutral, U is linearly separable in S and Π, and V is linearly separable in τ and λ. All the same, the significance of information asymmetries in R&D procurement are highlighted in Tan's work and he is able to show results similar in spirit to the body of the more standard research. For purposes of direct comparison with his research, we present a version of R&D procurement without the interim adverse selection problem, but with a Principal and Agent that may be risk averse.

Referring to Figure 4.1, $p(\tau)$ is a monitorable development expenditure made by the Agent which when combined with the outcome of Research, τ, yields $S(\tau, p)$. Gross compensation to the Agent is $t(\tau)$; however, the net compensation, analogous to the transfer in the one period model, is (t - p). The model and the nomenclature employed

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[39] Tan's physical production environment is quite similar, including an equivalent definition of off-the-shelf technology, τ_0.

[40] In Section 4.5, we will examine the effect of an unobservable Research outcome.

are the same as in section 4.1 except that an interim production stage has been added and the agent's utility function must account for the new definition of compensation. Thus;

> we suppress θ by viewing $\tilde{\tau}$ as a random variable with distribution $F(\tau, \lambda)$ and finite support $[\tau_o, \bar{\tau}]$. Given a distribution of θ, $F(\tau, \lambda)$ is the distribution induced on $\tilde{\tau}$ via the relationship $\tilde{\tau} = \tau(\lambda, \theta)$. Further, assume that F is convex in λ; i.e., $F_\lambda < 0$, $F_{\lambda\lambda} > 0$.

$$S = S(\tau, t(\tau)),\ S_i > 0,\ S_{ii} \le 0, \text{ and } S_{\tau t} \ge 0$$

$$V = v(t(\tau) - p(\tau)) - \psi(\lambda),\ U = U[S - t(\tau)].$$

Incorporating the interim production of τ, the analysis proceeds as follows:

Agent's Problem:

$$\text{ICC: } \frac{d}{d\lambda}\left\{\int [v(t - p) - \psi(\lambda)]fd\tau\right\} = 0 \Rightarrow \int vf_\lambda d\tau - \psi' = 0 \qquad 4.18$$

Principal's Agency Constrained Problem:

$$J = \int Ufd\tau + \gamma\int [v - \psi]fd\tau + \mu\left[\int vf_\lambda d\tau - \psi'\right] + \delta\lambda \qquad 4.19$$

Necessary Condition for an optimal λ

$$\frac{dJ}{d\lambda}: \int Uf_\lambda d\tau + \mu\left[\int vf_{\lambda\lambda} d\tau - \psi''\right] = -\delta \qquad 4.20$$

Integrating by parts yields

$$-\int F_\lambda U'\left[S_\tau + p'S_p - t'\right]d\tau - \mu\left[\int F_{\lambda\lambda} v'(t' - p')d\tau + \psi''\right] = -\delta \qquad 4.21$$

Necessary Condition for an optimal $t(\tau)$

$$\frac{dJ}{dt}: -U' + \gamma v'f + \mu v'f_\lambda = 0 \ \forall\tau$$

$$\frac{U'}{v'} = \gamma + \mu\frac{f_\lambda}{f} \ \forall\tau \qquad 4.22$$

Necessary Condition for an optimal $p(\tau)$

$$\frac{dJ}{dp} \Rightarrow \frac{S_p U'}{v'} = \gamma + \mu\frac{f_\lambda}{f} \ \forall\tau \qquad 4.23$$

Comparing (4.22) with (4.23) yields

$$S_p = 1 \ \forall\tau \qquad 4.24$$

Differentiating each side of (4.24) with respect to τ yields

$$S_{\tau p} + p'S_{pp} = 0 \ \forall\tau$$

$$p' = -\frac{S_{\tau p}}{S_{pp}} \geq 0 \qquad 4.25$$

Differentiating each side of (4.22) w.r.t τ and substituting for p' using (4.25) yields

$$v'\left[U''\left(S_\tau + p'S_p - t'\right)\right] - v''(t' - p')U' = \mu v'^2 \frac{d}{d\tau}\left(\frac{f_\lambda}{f}\right) \qquad 4.26$$

Substituting in (4.24) and rearranging yields

$$t' = p' + \frac{v'S_\tau U'' - \mu v'^2 \, {}^{d}\!/_{d\tau}\left({}^{f_\lambda}\!/_{f}\right)}{v'U'' + v''U'} \geq p' \geq 0 \qquad 4.27$$

From (4.21), as with the standard moral hazard problem illustrated in section 4.1, a sufficient condition for the Agent's maximization problem is that the transfer be positively monotonic. From (4.27) it is obvious that:

$$\left(t' - p'\right) \geq 0 \ \forall\tau \qquad 4.28$$

Similarly, from (4.21) and (4.24), a sufficient condition for an interior maximization to the Principle's problem is

$t' - p' \leq S_\tau$,

which can be expressed in terms of the Agent's relative risk aversion and the degree of moral hazard:

$$-\frac{v''}{v'} \geq \mu v'\left[\frac{{}^{d}\!/_{d\tau}\left({}^{f_\lambda}\!/_{f}\right)}{S_\tau U'}\right] \forall\tau \ . \qquad 4.29$$

(4.29) is markedly similar to (4.9), and is also an overly restrictive sufficient condition. We may now pose a theorem for two stage, single component production analogous to Theorem 4.1 for one stage, single component production.

Theorem 4.2: Given condition (4.29) or Assumption 3.1, the candidate solution to the R&D production of the complete item represented by the first order conditions [(4.20), (4.22), and (4.23)] is the unique optimum and has a form analogous to the Fixed Price/Performance Award contract.

Proof: Same as in Theorem 4.1. **QED**

Commentary
Theorems 4.1 and 4.2 show that production with R&D of the complete/marketable item adds computational but not substantive complexity to the standard optimal contracting outcomes.

4.4: Two Stage R&D Subcomponent Production

In this section we analyze the full model illustrated in Figure 4.1, with both two stage and subcomponent production. The nomenclature used is the same as in section 4.3 except that subcomponent production rather than complete production is modeled; namely, $U = U[S(\tau, p(\tau)), \Pi]$. Analysis proceeds in the now familiar fashion:

Agent's Problem:

$$\text{ICC: } \frac{d}{d\lambda}\left\{\int \left[v(t - p) - \psi(\lambda)\right] f d\tau\right\} = 0 \Rightarrow \int v f_\lambda d\tau - \psi' = 0 \qquad 4.30$$

Principal's Agency Constrained Problem:

$$J = \int U f d\tau + \gamma \int \left[v - \psi\right] f d\tau + \mu\left[\int v f_\lambda dS - \psi'\right] \qquad 4.31$$

The necessary condition for an optimum in λ:

$$\frac{dJ}{d\lambda}: \int Uf_\lambda d\tau + \mu\left[\int vf_{\lambda\lambda}\, d\tau - \psi''\right] = 0 \tag{4.32}$$

Integrating by parts (4.32) becomes

$$-\int F_\lambda\left[S_\tau U_S + p'S_pU_S - t'U_\pi\right]d\tau - \mu\left[\int F_{\lambda\lambda}\, v'(t' - p')d\tau + \psi''\right] = 0 \tag{4.33}$$

The necessary conditions for optimal R&D price and Development cost functions are:

$$\frac{dJ}{dt} \Rightarrow \frac{U_\pi}{v'} = \gamma + \mu\frac{f_\lambda}{f} \quad \forall\tau \tag{4.34}$$

$$\frac{dJ}{dp} \Rightarrow \frac{S_pU_S}{v'} = \gamma + \mu\frac{f_\lambda}{f} \quad \forall\tau \tag{4.35}$$

Combining (4.34) and (4.35) yields

$$S_pU_S = U_\pi \quad \forall\tau \tag{4.36}$$

Differentiating 4.36 with respect to τ yields

$$p' = \frac{S_{\tau p}U_S + S_\tau S_pU_{SS} - S_\tau U_{S\pi} + t'\left(U_{\pi\pi} - S_pU_{S\pi}\right)}{S_pU_{S\pi} - S_{pp}U_S - S_p^2U_{SS}} \quad \forall\, \tau \tag{4.37}$$

Differentiating (4.34) with respect to τ yields

$$v'\left[\left(S_\tau + p'S_p\right)U_{S\pi} - t'U_{\pi\pi}\right] - v''(t' - p')U_\pi = \mu v'^2\frac{d}{d\tau}\left(\frac{f_\lambda}{f}\right) \quad \forall\, \tau \tag{4.38}$$

Rearranging (4.38), we get

$$p'\left[v'S_pU_{S\pi} + v''U_\pi\right] - t'\left[v'U_{\pi\pi} + v''U_\pi\right] = \mu v'^2\frac{d}{d\tau}\left(\frac{f_\lambda}{f}\right) - v'S_\tau U_{S\pi} \tag{4.39}$$

(4.37) and (4.38) can be placed in matrix form as

$$\begin{vmatrix} 1 & B \\ C & D \end{vmatrix}\begin{vmatrix} p' \\ t' \end{vmatrix} = \begin{vmatrix} E \\ F \end{vmatrix} \quad \text{where}$$

$$B = -\frac{\left[U_{\pi\pi} - S_pU_{S\pi}\right]}{\left[S_pU_{S\pi} - S_{pp}U_S - S_p^2U_{SS}\right]} \geq 0\,, \quad E = \frac{S_{\tau p}U_S + S_\tau S_pU_{SS} - S_\tau U_{S\pi}}{\left[S_pU_{S\pi} - S_{pp}U_S - S_p^2U_{SS}\right]}$$

$C = v'S_pU_{S\pi} + v''U_\pi$, $D = -\left[v'U_{\pi\pi} + v''U_\pi\right] \geq 0$, and $F = \mu v'^2 \frac{d}{d\tau}\left(\frac{f_\lambda}{f}\right) - v'SU_{S\pi}$

Recalling that net compensation (t - p) is the critical contractual concern, applications of Cramer's Rule and rearrangement yield

$$t' - p' = \frac{\mu v'^2 \, d/_{d\tau}\left({}^{f_\lambda}/_{f}\right)\Omega - v'\left[S_\tau U_{S\pi}\left(S_pU_{S\pi} - S_{pp}U_S\right) + S_{\tau p}U_S\left(S_pU_{S\pi} - U_{\pi\pi}\right)\right]}{v'\left[U_{\pi\pi}\left(S_{pp}U_S + S_p^2U_{SS}\right) - S_p^2U_{S\pi}^2\right] - v''\Omega} \quad \forall\tau \qquad 4.40$$

where $\Omega = 2S_pU_{S\pi} - S_{pp}U_S - S_p^2U_{SS} - U_{\pi\pi} \geq 0$

Commentary

The inclusion of subcomponent production prevents (4.40) from being signed. This is true even if one assumes risk neutrality for both principal and agent. Thus, the complication added to the standard optimal contracting problem is more than a matter of computational haze; the addition of subcomponent considerations fundamentally affects contracting decisions.

From (4.33) and (4.36), sufficient conditions for maximization are

$$(t' - p') \leq \frac{S_\tau U_S}{U_\pi} \quad \forall\tau \text{ from the Principal's concerns, and}$$

$$(t' - p') \geq 0 \quad \forall\tau \text{ from the Agent's.}$$

As with the one stage subcomponent production analyzed in section 4.2, these sufficient conditions are not discernible from the necessary conditions on the candidate optimum contract (4.40). The complete lack of apparent monotonicity in (4.40) is important, intuitive, and essentially the same as in the one period case. Simply put, the profit seeking agent's basic desire for a contact which is increasing in output may not be reconcilable with the principal's fundamental intent to 'balance' the subcomponent inputs to overall production.

The optimal subcomponent R&D contracts which can, but need not necessarily result from the first order conditions to the Principal's Problem [(4.32), (4.34), and (4.35)] are essentially those illustrated in Figures 4.3 through 4.6. Even though the possible optimum contracts have the same characteristics with or without interim production, there is a significant reason for a principal organizing subcomponent production to be concerned with the outcome of an interim production step if one exists -- Knowledge of the outcome of interim production improves the principal's ability to optimally balance production decisions for other subcomponents that are being concurrently produced. Thus the ability to observe the outcome of interim production is significant to the optimal contracting decision.

4.5 The Relevance of the Observable

Assume that the outcome of interim production, τ, is not observable. Instead after Research is concluded, the agent states an outcome, $\hat{\tau} = \tau - \varepsilon$; the principal provides the payment $t(\hat{\tau})$; and the agent produces $S(\tau, p^*)$. The Research outcome will be understated ($\varepsilon > 0$) if the agent benefits from such a statement. This sequence is illustrated in Figure 4.7 which is equivalent to Figure 4.1 with the addition of the agent's transmittal of $\hat{\tau}$ to the principal. The extent of understatement is bound by the principal's assumed ability to enforce the outcome of subcomponent production -- Actual production must equal that claimed; mathematically,

$$S\left(\tau, p^*\right) \equiv S\left(\hat{\tau}, p(\hat{\tau})\right) \qquad 4.41$$

Applying the implicit function theorem to (4.41), we know that there exists a $p^*(\varepsilon)$ and that

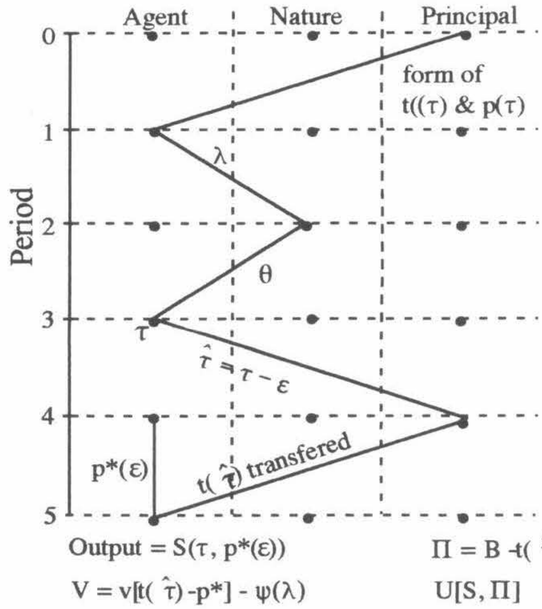
$$p'^* = \frac{S_\tau + p'S_p}{S_p}. \quad 4.42$$

We can now characterize misrepresentation when τ is not observable:

$$\pounds = v\left[t(\tau - \varepsilon) - p^*(\tau - \varepsilon)\right] - \psi(\lambda) + \rho\varepsilon$$

$$\frac{\partial \pounds}{\partial \varepsilon}: \; -v\left[t' - p'^*\right] = -\rho$$

Figure 4.7: Profit Seeking Agent without an Observable Research Outcome



Substituting in the expression for p'^* from (4.42) and rearranging:

$$t' - p' = \frac{S_\tau}{S_p} + \frac{\rho}{v'} \quad 4.43$$

Note that if $\rho > 0$, then $\varepsilon = 0$, $\hat{\tau} = \tau$, and the lack of an observable is irrelevant. The condition on (t' - p') for this follows directly from (4.43)

$$t' - p' > \frac{S_\tau}{S_p} \quad 4.44$$

Theorem 4.3: Whether organizing production directly for the complete final good [section 4.3] or for subcomponents to the final good [section 4.4], no interior optimal ICDR contract (i.e., a contract that includes R&D, $\lambda^* > 0$) based on a stated but unobserved Research outcome is possible.

Proof: For Complete Production [Section 4.3]

A condition of the optimization in section 4.3 (4.24) was that $S_p = 1$ for all τ; thus, for $\hat{\tau} = \tau$, condition (4.44) becomes $t' - p' > S_\tau$ which over all τ violates the necessary condition (4.21) for λ being an optimum.

For Subcomponent Production [Section 4.4]

[Proof by contradiction] Posit that for some τ, the agent states the truth, $\hat{\tau} = \tau$. Posit that for this same τ, an optimal compensation function $[t(\tau) - p(\tau)]$ has the property that

$(t' - p') \leq \frac{S_\tau U_S}{U_\pi}$; i.e., the principal's utility is greater than it would have been at $\tau - \partial\tau$. Therefore, at this τ, by (4.44), $\frac{S_\tau U_S}{U_\pi} > \frac{S_\tau}{S_p} \Rightarrow S_p > \frac{U_\pi}{U_S}$. Were there no agency concerns, the principal would determine optimum $p(\tau)$ by maximizing $U[S(\tau, p(\tau)), B - p(\tau)]$ which results in the condition that $S_p = \frac{U_\pi}{U_S}$. Any 'Cost of Agency' will cause $S_p < \frac{U_\pi}{U_S}$. This contradicts the assumption that the compensation function $[t(\tau) - p(\tau)]$ was an optimal contract. This contradiction holds over all τ. **QED**

Thus, if the outcome of Research, τ, is not observable, then an optimum incentive compatible contracting arrangement must be conditioned on the final outcome of subcomponent production, S, as in sections 4.1 and 4.2.

4.6 Summary

Under complete production [sections 4.1 and 4.3], conditions can be established such that the solutions to the first order conditions are contracts between principal and agent that optimally account for the agency concerns, assuming the Research outcome is observable. If the inclusion of a second production period is meant to adequately represent the Development stage of an R&D process [section 4.3], then we conclude that R&D adds nothing fundamental to the moral hazard problem. If, however, production influenced by R&D is more appropriately modeled with a subcomponent approach [sections 4.2 and 4.4], then we have shown that contracts with profit seeking agents that optimally account for moral hazard concerns may not result. Before searching for possible third-best optima based on modifications to the solutions from sections 4.2 and 4.4 (as in Guesnerie and Laffont) examination of alternate production organizations is appropriate and constitutes the analysis of Chapter 5.[41]

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[41]Roger Guesnerie and Jean-Jacques Laffont, "A Complete Solution to a Class of Principal-Agent Problems with an Application to the Control of a Self-Managed Firm," *Journal of Public Economics*, vol. 25, 1985, pages 329-369.

Chapter 5: The Effects of Moral Hazard on R&D Procurement from a Performance Seeking Agent

5.0 Justification of Performance Seeking Agency

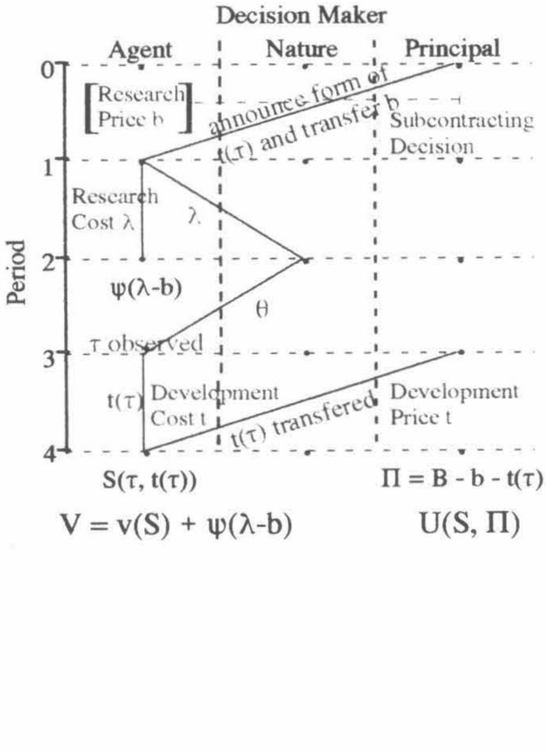
When the government or a managing principal of the government contracts for a new subcomponent of a scientific program or a new technology element to a scientific endeavor, it often seeks out the effort of a Scientist in the field of interest. This Scientist becomes the agent of the government or the government's managing principal and is funded to undertake the R&D, usually under the condition that he may not directly profit from the work (beyond an agreed salary). Such a condition is satisfactory for the Scientist as the career impact of being involved is substantial.

Alternatively, consider a manager in a large company or government research lab who has been given the assignment to conduct the R&D of a new subcomponent to some larger task. Such a manager agent will garner substantial career advancement potential from a successful R&D effort. Agents such as these are clearly motivated by the performance of the subcomponent that they have been contracted to innovate.

Figure 5.1 illustrates R&D contracting to a performance seeking agent. The organization of production differs from that of Figure 4.1 as follows:

> This type of agent may have limited access to capital markets; thus, initial funds, b, may be provided to the agent as a Research Price.
>
> The price of Development, t, is transferred to the agent without any additional compensation.
>
> The only source of monetary compensation for the agent is (b-λ).
>
> Disutility of forgoing compensation, 0≤(b-λ)<b, or of providing independent funding, (b-λ)<0, is captured by ψ(λ-b) in the utility function, V.

Figure 5.1: Decision Flow if Contracting with a Performance Seeking Agent



The basic information asymmetry remains unchanged from Chapter 4; the outcome of Research, τ, is observed by both principal and agent, but the inputs to Research, λ and θ, are observed only by the agent. The agent may choose to take advantage of the moral hazard inherent in the Research portion of the task by reporting a Research cost of λ while having actually expended $\lambda^* < \lambda$ and retaining $(b - \lambda^*) > (b - \lambda)$ for himself. In the case of a Scientist agent the motivation for skimming the quantity $(\lambda - \lambda^*)$ may take the form of padding other grants, adding equipment, augmenting staff, 'buying-out' teaching requirements, travel, etc... For a manager, likely uses of skimming include the pursuit or retention of other business (a portfolio management use) or the ever suspected act of 'empire building' within the larger organization to which the manager belongs.

Implicit in the structure of the process illustrated in Figure 5.1 is that the principal can enforce the outcome, S, of the subcomponent R&D production process. This means that the level of S delivered must be greater than or equal to the level that would result from the observed technology, τ, and the transferred Development price $t(\tau)$, else some binding and effective form of punishment will be inflicted on the agent. If the principal cannot credibly punish the agent for a lower performance output, then the contract cannot be enforced and the organizational problem, as stated, is ill-defined.

The nomenclature and functional assumption for the performance seeking agent are very similar to section 4.4 with the exclusion of $p(\tau)$ and the necessary modifications to the agent's utility, V, amounting to $v' > 0$, $v'' < 0$, $\psi' < 0$, $\psi'' < 0$. Analysis proceeds in two sequential steps: Full Information and Incomplete Information.

<u>5.1 Subcontracting under Full Information</u>

The agent's Participation Constraint

$$\int \left[v\left[S(\tau,\ t(\tau)) \right] \ +\ \psi(\lambda - b) \right] f(\tau,\ \lambda) d\tau \ \geq\ \kappa \qquad 5.1$$

The Principal's problem may then be formed as

$$\underset{b,\lambda,t(\tau)}{J} = \int U[S(\tau,\ t(\tau)),\ B - b - t(\tau)]f(\tau,\ \lambda)d\tau\ +\ \gamma\left[\int [v\ +\ \psi]f(\tau,\ \lambda)d\tau\ -\ \kappa\right] + \eta b\ +\ \rho\lambda \qquad 5.2$$

The First Order Conditions are:

$$\frac{\partial J}{\partial b}:\ -\int U_{\pi}fd\tau\ -\ \gamma\psi'\ +\ \eta\ = 0 \qquad 5.3$$

$$\frac{\partial J}{\partial \lambda}:\ \int Uf_{\lambda}d\tau\ +\ \gamma\left[\int vf_{\lambda}d\tau\ +\ \psi'\right]\ +\ \rho\ = 0 \qquad 5.4$$

Pointwise optimization of J relative to t yields:

$$\frac{S_tU_S\ -\ U_{\pi}}{S_tv'}\ =\ -\ \gamma\quad \forall\,\tau \qquad 5.5$$

Lemma 5.1: $U_{\pi} - S_tU_S > 0$ for all τ.

Proof: Immediate from $\gamma > 0$. **QED**

The third first order condition (5.5) can be used to obtain the first derivative of the optimal contract by differentiating each side relative to τ.

$$t'\ =\ -\ \frac{S_{\tau}S_t\left[v'(S_tU_{SS}\ -\ U_{S\pi})\ -\ v''(S_tU_S\ -\ U_{\pi})\right]\ +\ v'S_{\tau t}U_{\pi}}{S_t^2\left[v'(S_tU_{SS}\ -\ U_{S\pi})\ -\ v''(S_tU_S\ -\ U_{\pi})\right]\ -\ v'S_t(S_tU_{S\pi}\ -\ U_{\pi\pi})\ +\ v'S_{tt}U_{\pi}} \qquad 5.6$$

Note that t' may be <=> 0.

Lemma 5.2: The contract under complete information has the property that

$$t'\ >\ -\ \frac{S_{\tau}}{S_t}\quad \forall\,\tau.$$

Proof: From 5.6:

$$t'\ =\ -\ \frac{S_{\tau}X\ +\ A}{S_tX\ +\ B},\ \text{where}\ \begin{cases} X\ =\ S_t\left[v'(S_tU_{SS}\ -\ U_{S\pi})\ -\ v''(S_tU_S\ -\ U_{\pi})\right]\ <\ 0 \\ A\ =\ v'S_{\tau t}U_{\pi}\ >\ 0 \\ B\ =\ v'\left[S_{tt}U_{\pi}\ -\ S_t(S_tU_{S\pi}\ -\ U_{\pi\pi})\right]\ <\ 0 \end{cases} \qquad 5.7$$

$$t'\ =\ -\ \frac{S_{\tau}X}{S_tX\ +\ B}\ -\ \frac{A}{S_tX\ +\ B}\ >\ -\ \frac{S_{\tau}X}{S_tX\ +\ B}\ >\ -\ \frac{S_{\tau}}{S_t}.\quad \textbf{QED} \qquad 5.8$$

Lemma 5.3: The contract under complete information has the property that

$$t' \leq -\frac{S_{\tau t}}{S_{tt}} \quad \forall \tau.$$

Proof:

$$t' = -\frac{Y + v' S_{\tau t} U_{\pi}}{C + v' S_{tt} U_{\pi}}, \tag{5.9}$$

$$\text{where } \begin{cases} Y = S_{\tau} S_{t}\left[v'(S_t U_{SS} - U_{S\pi}) - v''(S_t U_S - U_{\pi})\right] < 0 \\ C = S_t^2\left[v'(S_t U_{SS} - U_{S\pi}) - v''(S_t U_S - U_{\pi})\right] - v' S_t (S_t U_{S\pi} - U_{\pi\pi}) < 0 \end{cases}$$

$$t' = -\frac{Y}{C + v' S_{tt} U_{\pi}} - \frac{v' S_{\tau t} U_{\pi}}{C + v' S_{tt} U_{\pi}} < -\frac{v' S_{\tau t} U_{\pi}}{C + v' S_{tt} U_{\pi}} < -\frac{S_{\tau t}}{S_{tt}} \quad \textbf{QED} \tag{5.10}$$

Theorem 5.1: If $S(\tau, t)$ is separable in its arguments (i.e., $S_{\tau t} = 0$), then the contract under complete information has the property that $t' \leq 0$ for all τ. [A pure margin contract]

Proof: Immediate from **L5.2** and **L5.3**. **QED**

Assumption 5.1: The solution, t^*, to the first order conditions has the property

$$t' < \frac{S_{\tau} U_S}{U_{\pi} - S_t U_{\pi}} \quad \forall \tau.$$

Theorem 5.2: Given Lemma 5.2 and Assumption 5.1, the contract under complete information has the property that for each increase in τ, both the Principal and the Agent are made better off. This property is captured by the following inequality:

$$-\frac{S_{\tau}}{S_t} < t' < \frac{S_{\tau} U_S}{U_{\pi} - S_t U_S} \quad \forall \tau$$

Proof: That the inequality implies that both would be better off over all $d\tau$ is shown

$$\frac{dS}{d\tau} = S_{\tau} + t' S_t \quad \therefore \quad t' > -\frac{S_{\tau}}{S_t} \Rightarrow \frac{dS}{d\tau} > 0 \tag{5.11}$$

$$\frac{dU}{d\tau} = S_{\tau} U_S - t'(U_{\pi} - S_t U_S) \quad \therefore \quad t' < \frac{S_{\tau} U_S}{(U_{\pi} - S_t U_S)} \Rightarrow \frac{dU}{d\tau} > 0. \quad \textbf{QED}$$

Corollary 5.1: If the relative risk aversion condition

$$-\frac{v''}{v'} \geq \frac{S_{\tau t}}{S_\tau S_t} + \frac{\Omega}{S_t U_\pi (U_\pi - S_t U_S)} \quad \forall\tau$$

$$\Omega = S_{tt} U_S U_\pi - S_t U_S (S_t U_{S\pi} - U_{\pi\pi}) + S_t U_\pi (S_t U_{SS} - U_{S\pi}) \leq 0 \;\; \forall\tau$$

holds, then Assumption 5.1 is satisfied and Theorem 5.2 holds:

Proof: Follows directly by establishing the condition on t' such that the Principal would be no better off with each increasing revelation in the observable τ.

$$t'\Big|_{\frac{dU}{d\tau}=0} = \frac{S_\tau U_S}{U_\pi - S_t U_S} \tag{5.12}$$

Set this as the maximum t' allowed relative to the candidate solution (5.6):

$$\frac{S_\tau U_S}{U_\pi - S_t U_S} \geq - \frac{S_\tau S_t\left[v'(S_t U_{SS} - U_{S\pi}) - v''(S_t U_S - U_\pi)\right] + v' S_{\tau t} U_\pi}{S_t^2\left[v'(S_t U_{SS} - U_{S\pi}) - v''(S_t U_S - U_\pi)\right] - v' S_t (S_t U_{S\pi} - U_{\pi\pi}) + v' S_{tt} U_\pi} \quad \forall\tau \tag{5.13}$$

Rearranging terms and separating out all v' and v" terms yields:

$$-v''(U_\pi - S_v U_S)\left[S_\tau S_t (U_\pi - S_v U_S) + S_\tau S_t^2 U_S\right] \geq v'\begin{bmatrix} S_\tau S_t^2 U_S (S_t U_{SS} - U_{S\pi}) - S_\tau S_t U_S (S_t U_{S\pi} - U_{\pi\pi}) + S_\tau S_{tt} U_S U_\pi \\ + S_{\tau t} U_\pi (U_\pi - S_t U_S) + S_\tau S_t (U_\pi - S_t U_S)(S_t U_{SS} - U_{S\pi}) \end{bmatrix} \quad \forall\tau \tag{5.14}$$

Cancellation and further rearrangement leads to the desired result:

$$-\frac{v''}{v'} \geq \frac{S_{\tau t}}{S_\tau S_t} + \frac{\Omega}{S_t U_\pi (U_\pi - S_t U_S)} \quad \forall\tau \tag{5.15}$$

$$\Omega = S_{tt} U_S U_\pi - S_t U_S (S_t U_{S\pi} - U_{\pi\pi}) + S_t U_\pi (S_t U_{SS} - U_{S\pi}) \leq 0 \;\; \forall\tau.$$ **QED**

Corollary 5.2: If U_{SS}, $U_{\pi\pi}$, $U_{S\pi}$, and v" = 0 [Tan's Assumptions], then

i. $t' = -\dfrac{S_{\tau t}}{S_{tt}} \;\; \forall\,\tau$

ii. $\dfrac{d}{d\tau}\left[U_\pi - S_t U_S\right] = \dfrac{d}{d\tau}\left[S_t v'\right] = 0 \;\; \forall\,\tau$

iii. Assumption 5.1 holds, implying that Theorem 5.2 and Corollary 5.1 hold.

Proof:

i. immediate from (5.6) {maximum slope by **L5.3**}

ii. $d/dt[U_\pi - S_t U_S]$

$$= t'\left[2S_t U_{S\pi} - U_{\pi\pi} - S_{tt}U_S - S_t^2 U_{SS}\right] + S_\tau U_{S\pi} - S_{\tau t}U_S - S_\tau S_t U_{SS} = 0 \qquad 5.16$$

$d/dt[S_t v']$

$$= t'\left[v''S_t^2 + v'S_{tt}\right] + v''S_\tau S_t + v'S_{\tau t} = 0 \qquad 5.17$$

iii. immediate from (ii) and **L5.1. QED**

Commentary

Corollary 5.2 provides a useful comparison to the existing R&D contracting literature when one adds the element of an agent motivated by the capability of his output. Under conditions of optimum risk sharing, the optimum contract has the standard properties of positive monotonicity in the observable and uniformly increasing utilities for Principal and Agent with each increase in the observable. These results suggest that the new type of agency introduced here does not, in and of itself, fundamentally affect contracting.

The R&D production decision is made relative to available, known subcomponents that do not require R&D. By assumption, the subcomponent S has been chosen to undergo R&D while all other subcomponents are purchased directly using Π. Therefore, we know that the expected value of the Principal's utility, E[U], is greater than the known solution, U_o, or else the decision to perform R&D on subcomponent S would not have been made.

Comparing the model in section 5 to those in section 4, recall that with subcomponent production (sections 4.2 and 4.4), optimal risk sharing under complete information, $\mu = 0$, did not necessarily result in both the Principal and Agent being better off over all levels of output. This was shown with complete production (sections 4.1 and 4.3). Further, it could not definitely be shown in sections 4.2 and 4.4 that the full (or incomplete) information solution resulted in either the Principal or Agent being better off in expectation. Though Theorem 5.2, Corollary 5.1 and Corollary 5.2 we have shown conditions under which the R&D model of section 5 exhibits the standard qualities of optimal risk sharing under complete information. By Theorem 5.3 we will establish that both Principal and Agent are generally better off in expectation under full information for the model of subcomponent R&D production examined in section 5.

Theorem 5.3: Given Assumption 3.1, if U_{SS}, $U_{\pi\pi}$, $v'' \leq 0$, and $U_{S\pi} \geq 0$, then both the Principal and Agent are better off over all τ.

Proof:

That the Agent is better off over all τ is provided by Lemma 5.2 and Theorem 5.2. That the Principal is better off is shown through examination of condition (5.4) and the initial assumption that $E[U] > U_o$.

$$\text{Recall (5.4): } \frac{\partial J}{\partial \lambda}: \int Uf_\lambda d\tau + \gamma\left[\int vf_\lambda d\tau + \psi'\right] + \rho = 0$$

By Assumption 3.1, $\rho = 0$ and the participation constraint (5.1) holds; therefore $\gamma > 0$. Now define the Marginal R&D case (MR&D) as the solution to conditions (5.2, 5.3, and 5.4) that results in

$$\int U\left[S(\tau, t(\tau)), B - b - t(\tau)\right] f(\tau, \lambda) d\tau \equiv U\left(S_o, B - P_{S_o}\right)$$

$$\therefore \int Uf_\lambda d\tau \Big|_{MR\&D} = 0 \xrightarrow{(5.4)} \left[\int vf_\lambda d\tau + \psi'\right]\Big|_{MR\&D} = 0$$

Now examine the nature of MR&D for a differential increase in λ:

$$\frac{\partial}{\partial \lambda}\left[\int vf_\lambda d\tau + \psi'\right] = \int vf_{\lambda\lambda} d\tau + \psi'' = -\int F_{\lambda\lambda} v'(S_\tau + t' S_t) d\tau + \psi'' \overset{L5.2}{<} 0$$

Therefore, from (5.4), $\int Uf_\lambda d\tau > 0$ for R&D efforts above MR&D

Now assume that at MR&D the Principal opts for U_o rather than for E[U]; therefore

$$\int Uf_\lambda d\tau > 0 \text{ for all R\&D undertaken} \Rightarrow -\int F_\lambda\left(\frac{\partial U}{\partial \tau}\right) d\tau > 0,$$

which implies that the Principal is better off in expectation for all R&D undertaken. **QED**

5.2 Subcontracting under Incomplete Information

In this section, the information asymmetry illustrated in Figure 5.1 and common to the analyses in Chapter 4 is considered for the performance seeking agent. This asymmetry should result in a moral hazard agency concern as the performance interests of the agent do not perfectly overlap those of the principal.

The Agent's problem is to choose λ to maximize

$$£_1 = \int \left[v\left[S(\tau,\ t(\tau))\right] + \psi(\lambda - b)\right] f(\tau,\ \lambda) d\tau \qquad 5.18$$

$$\frac{\partial £_1}{\partial \lambda} : \int \left[(v + \psi) f_\lambda + \psi' f \right] d\tau = \int v f_\lambda d\tau + \psi' = 0 \quad \{ICC\} \qquad 5.19$$

As before, the participation constraint is

$$\int \left[v\left[S(\tau,\ t(\tau))\right] + \psi(\lambda - b)\right] f(\tau,\ \lambda) d\tau \geq \kappa \quad \{PC\}.$$

The Agency Constrained Principal's problem

$$\underset{b,\lambda,t(\tau)}{J} = \int U[S,\ \pi] f(\tau,\ \lambda) d\tau + \gamma\left[\int [v + \psi] f(\tau,\ \lambda) d\tau - \kappa\right] + \mu\left[\int v f_\lambda d\tau + \psi'\right] + \eta b + \rho\lambda \qquad 5.20$$

First Order Conditions

$$\frac{\partial J}{\partial b}: \ -\int U_\pi f d\tau - \gamma\psi' - \mu\psi'' + \eta = 0 \qquad 5.21$$

$$\frac{\partial J}{\partial \lambda}: \ \int U f_\lambda d\tau + \mu\left[\int v f_{\lambda\lambda} d\tau + \psi''\right] + \rho = 0 \qquad 5.22$$

Integration of (5.22) by parts yields:

$$-\int F_\lambda\left[S_\tau U_S - t'(U_\pi - S_t U_S)\right] d\tau + \mu\left[\psi'' - \int F_{\lambda\lambda} v'[S_\tau + t' S_t] d\tau\right] + \rho = 0 \qquad 5.23$$

Pointwise optimization of J relative to t yields:

$$\frac{S_t U_S - U_\pi}{S_t v'} = -\gamma - \mu\frac{f_\lambda}{f} \quad \forall \tau \qquad 5.24$$

Differentiating (5.24) with respect to τ yields the expression for t':

$$t' = -\frac{S_\tau S_t\left[v'(S_t U_{SS} - U_{S\pi}) - v''(S_t U_S - U_\pi)\right] + v' S_{\tau t} U_\pi + \mu (v' S_t)^2 \frac{\partial}{\partial \tau}\left(\frac{f_\lambda}{f}\right)}{S_t^2\left[v'(S_t U_{SS} - U_{S\pi}) - v''(S_t U_S - U_\pi)\right] - v' S_t (S_t U_{S\pi} - U_{\pi\pi}) + v' S_{tt} U_\pi} \quad 5.25$$

Note that t' may be <=> 0.

In order to prove that these first order conditions describe the optimal solution to the R&D problem illustrated in Figure 5.1 and in order to characterize the incentive compatible contract $t(\tau)$, a series of lemmas and theorems follows:

Lemma 5.4: In the incomplete information case, as with complete information, $S_t U_S - U_\pi \leq 0$ for all τ.

Proof: Define ¥ as the space of (S, Π) pairs on which the Principal's utility may be assessed. Also define t^* as a candidate for the optimal contract from the first order conditions to Model III. For any true t^*, we know that

i. $\dfrac{S_t U_S - U_\pi}{S_t v'} = -\gamma - \mu \dfrac{f_\lambda}{f}$

ii. $\dfrac{f_\lambda}{f}$ <=> 0 depending on τ

iii. $\therefore\ S_t U_S - U_\pi < 0$ for some τ regardless of μ <=> 0.

The proof proceeds by contradiction:

Assume that given t^*, for some τ, $S_t U_S - U_\pi > 0$. Then from (iii) there is a point B in ¥ where $S_t U_S - U_\pi = 0$. Further, characterize t^* by the intervals in ¥ around B

over [A, B] $t^*(\tau)$ s.t. $S_t U_S - U_\pi \leq 0$

over (B, C] $t^*(\tau)$ s.t. $S_t U_S - U_\pi > 0$

Now consider $t^{**} \equiv \begin{cases} t^* \text{ over } [A, B] \\ \text{s.t. } S_t U_S - U_\pi = 0 \text{ over } (B, C] \end{cases}$

Over (B, C] note that both Principal and Agent are better off with t^{**} then with t^*; therefore t^* cannot be the optimal solution. This is a contradiction, and thus

$S_t U_S - U_\pi \leq 0$ for all τ. **QED**

Theorem 5.4: $\mu > 0$; i.e., there is a moral hazard agency contracting concern.

Proof: Assume the contrary; i.e., $\mu \leq 0$. Denote by $\hat{t}(\tau)$ the transfer required under the optimum risk sharing condition (5.5) to result in the incomplete information participation shadow price defined by

$$\gamma = -\left[\frac{S_t U_S - U_\pi}{S_t v'} + \mu \frac{f_\lambda}{f}\right] \forall \tau$$

for $\tau \in \langle \tau | f_\lambda(\tau,\lambda) > 0 \rangle$

$$-\left[\frac{S_t U_S - U_\pi}{S_t v'}\right] \leq \gamma = -\left[\frac{\hat{S}_t \hat{U}_S - \hat{U}_\pi}{\hat{S}_t \hat{v}'}\right] \tag{5.26}$$

$$\left[\frac{U_\pi - S_t U_S}{S_t v'}\right] \leq \left[\frac{\hat{U}_\pi - \hat{S}_t \hat{U}_S}{\hat{S}_t \hat{v}'}\right] \Rightarrow \begin{cases} \hat{t}(\tau) \geq t(\tau) \\ \hat{\pi} \leq \pi \\ \hat{S} \geq S \end{cases} \tag{5.27}$$

for $\tau \in \langle \tau | f_\lambda(\tau,\lambda) < 0 \rangle$

$$\left[\frac{U_\pi - S_t U_S}{S_t v'}\right] \geq \left[\frac{\hat{U}_\pi - \hat{S}_t \hat{U}_S}{\hat{S}_t \hat{v}'}\right] \Rightarrow \begin{cases} \hat{t}(\tau) \leq t(\tau) \\ \hat{\pi} \geq \pi \\ \hat{S} \leq S \end{cases} \tag{5.28}$$

for $\tau \in \langle \tau | f_\lambda(\tau,\lambda) = 0 \rangle$

$$\left[\frac{U_\pi - S_t U_S}{S_t v'}\right] = \left[\frac{\hat{U}_\pi - \hat{S}_t \hat{U}_S}{\hat{S}_t \hat{v}'}\right] \Rightarrow \begin{cases} \hat{t}(\tau) = t(\tau) \\ \hat{\pi} = \pi \\ \hat{S} = S \end{cases} \tag{5.29}$$

Combining these results with Lemma 5.1, we have

$$\int U f_\lambda \, d\tau \geq \int \hat{U} f_\lambda \, d\tau \tag{5.30}$$

Integrating by parts

$$\int \hat{U} f_\lambda \, d\tau = -\int F_\lambda \left[\frac{d\hat{U}}{d\tau}\right] d\tau \xrightarrow{\text{Theorem 5.3}} > 0 \tag{5.31}$$

$$\therefore \int U f_\lambda d\tau > 0 \qquad 5.32$$

This implies, by the assumption that the agent's problem (5.22) has an interior solution, that the coefficient of μ must be negative; thus requiring μ > 0. This is a contradiction.

$\therefore \mu > 0$. **QED**

Lemma 5.5: Given Lemma 5.2 and Theorem 5.4, $t' > -\frac{S_\tau}{S_t} \ \forall \tau$ [a sufficient condition for (5.19) to characterize the solution of the Agent's problem]

Proof: Recall the expression for t' under incomplete information (5.25)

$$t' = -\frac{S_\tau S_t\left[v'(S_t U_{SS} - U_{S\pi}) - v''(S_t U_S - U_\pi)\right] + v' S_{\tau t} U_\pi + \mu (v' S_t)^2 \frac{\partial}{\partial \tau}\left(\frac{f_\lambda}{f}\right)}{S_t^2\left[v'(S_t U_{SS} - U_{S\pi}) - v''(S_t U_S - U_\pi)\right] - v' S_t (S_t U_{S\pi} - U_{\pi\pi}) + v' S_{tt} U_\pi} \quad \forall \tau$$

This can be rewritten as

$$t' = -\frac{S_\tau X + A}{S_t X + B} \ \forall \tau, \text{ where } \begin{cases} X = S_t\left[v'(S_t U_{SS} - U_{S\pi}) - v''(S_t U_S - U_\pi)\right] < 0 \\ A = v' S_{\tau t} U_\pi + \mu (v' S_t)^2 \frac{\partial}{\partial \tau}\left(\frac{f_\lambda}{f}\right) > 0 \\ B = v'\left[S_{tt} U_\pi - S_t(S_t U_{S\pi} - U_{\pi\pi})\right] < 0 \end{cases} \qquad 5.33$$

$$t' = -\frac{S_\tau X}{S_t X + B} - \frac{A}{S_t X + B} > -\frac{S_\tau X}{S_t X + B} > -\frac{S_\tau}{S_t} \ \forall \tau. \ \textbf{QED} \qquad 5.34$$

Commentary

For subcomponent R&D production under profit seeking agency (section 4.3) we were unable to show that the contract resulting from the first order conditions had the property that the agent was better off for each differential increase in the Research outcome. This failing prohibited the establishment of any Theorem characterizing optimal R&D contracting with a profit seeking agent. Under performance seeking agency we have proven Lemma 5.5 which establishes that the agent is better off for each differential increase in the Research outcome. This result plays a pivotal role in the Theorems to follow.

Assumption 5.2: $t' < \dfrac{S_\tau U_S}{U_\pi - S_t U_\pi}$ for all τ. [The Principal is better off for each τ]

Theorem 5.5: Given Assumption 5.2 or Assumption 3.1, the solution $\{b^*, \lambda^*, t(\tau)^*\}$ derived from the first order necessary conditions to the Principal's problem (5.19) is the unique optimum solution and results in positive research investment [$\lambda > 0$].

Proof:

i. From (5.23) it is clear that Lemma 5.5 provides a sufficient condition for the Agent's optimization with respect to λ.

ii. Assumption 5.2 is a sufficient condition for concavity with respect to λ of the maximand in the Principal's optimization problem:

The second derivative of the maximand combined with **A5.2** yields

$$-\int F_{\lambda\lambda}\left[S_\tau U_S - t'(U_\pi - S_t U_S)\right]d\tau \leq 0$$

ii. The Principal's side of (5.21) is quasi-concave, the Agent's convex:

The maximum will occur in the interior. **QED**

Commentary

The optimal ICDR contract assured under Theorem 5.5 may take any of the forms illustrated in Figure 4.2. This should be apparent from Lemma 5.5 and Assumption 5.2. Thus, if we observe a pure margin contract let to a performance seeking agent we cannot automatically conclude that the production organization is sub-optimal as we can with a profit seeking agent.

Corollary 5.3: Assumption 5.2 and its role in Theorem 5.5 can be characterized by the relative risk aversion condition [Analogous to Corollary 5.1]:

$$-\frac{v''}{v'} \geq \frac{S_{\tau t}}{S_\tau S_t} + \mu\frac{v' S_t}{S_\tau U_\pi}\frac{d}{d\tau}\left(\frac{f_\lambda}{f}\right) + \frac{\Omega}{S_t U_\pi(U_\pi - S_t U_S)} \quad \forall\tau$$

$$\Omega = S_{tt}U_S U_\pi - S_t U_S(S_t U_{S\pi} - U_{\pi\pi}) + S_t U_\pi(S_t U_{SS} - U_{S\pi}) \leq 0 \ \forall\tau.$$

Proof: Immediate with the same approach as Corollary 5.1. **QED**

Commentary

Moral hazard agency concerns have been shown to pertain for R&D subcomponent production with a performance seeking agent (Theorem 5.4). Given that we accept the motivating assumption that the principal has decided to innovate S as opposed to all other subcomponents (Assumption 3.1, $\lambda^* > 0$), then we have shown that an optimal incentive compatible contract (b^*, $t^*(\tau)$) satisfies the first order conditions in the interior.

5.3 The Relevance of the Observable

Assume that τ is not observable. Instead after Research is concluded, the agent states an outcome, $\hat{\tau} = \tau - \varepsilon$; the principal provides the payment $t(\hat{\tau})$; and the Agent produces $S(\tau, t^*)$. This sequence is illustrated in Figure 5.2.

Definition of Enforcement:

$$S\left(\tau, t^*\right) \equiv S\left(\hat{\tau}, t(\hat{\tau})\right) \qquad 5.35$$

By the implicit function theorem, we know that there exists a $t^*(\varepsilon)$ and that

$$t'^* = \frac{S_\tau + t'S_t}{S_t}. \qquad 5.36$$

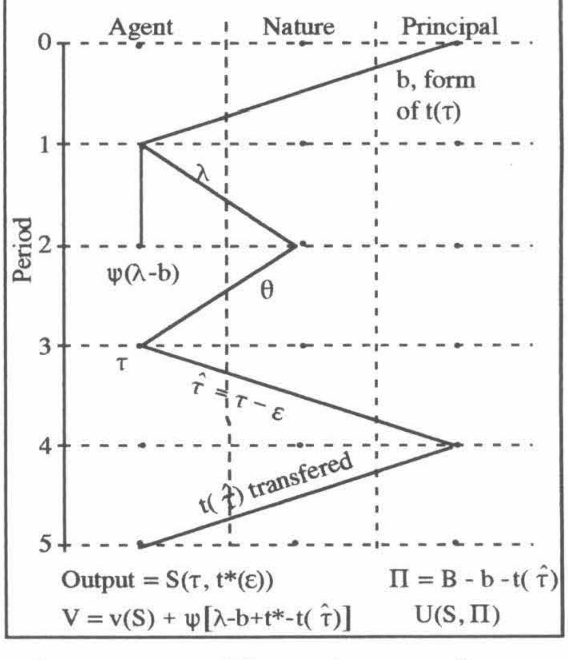
Characterization of misrepresentation when τ is not observable:

$$£ = v\left[S\left(\tau, t^*(\tau-\varepsilon)\right)\right] + \psi\left[t^*(\tau-\varepsilon) - t(\tau-\varepsilon)\right] + \rho\varepsilon$$

$$\frac{\partial £}{\partial \varepsilon}: -t'^* v'S_t - t'^*\psi' + t'\psi' = -\rho$$

$$t'\psi' - t'^*\left[v'S_t + \psi'\right] = -\rho$$

Figure 5.2: Interested Agent without an Observable Research Outcome



Substituting in the expression for t'^* from the enforcement condition and rearranging:

$$t' = -\frac{S_\tau}{S_t}\left[1 + \frac{\psi'}{v'S_t}\right] + \rho \qquad 5.37$$

Note that if $\rho > 0$, then $\varepsilon = 0$, $\hat{\tau} = \tau$, and the lack of an observable is irrelevant. The condition on t' for this follows directly from (5.37)

$$t' > -\frac{S_\tau}{S_t}\left[1 + \frac{\psi'}{v'S_t}\right], \text{ where we set } \Gamma = \left[1 + \frac{\psi'}{v'S_t}\right] \text{ and note that } \Gamma \leq 1 \qquad 5.38$$

From Lemma 5.5 we know that $t' > -\frac{S_\tau}{S_t}$; thus, Γ determines the relevance of the observable and can be thought of as $\left[1 + \frac{\text{Marginal Disutility of Revealing } \tau}{\text{Marginal Utility of Revealing } \tau}\right]$.

Therefore, Γ represents an agent attribute that affects whether or not interim adverse selection binds.

Theorem 5.6: When contracting with a performance seeking agent, an optimal ICDR R&D contract with an unobserved Research output is possible if, for all Research outcomes, the agent's marginal utility from skimming, $-\psi'$ is less than or equal to its marginal utility from not skimming, $v'S_t$.

Proof: Posit a candidate optimal $\tilde{t}(\tau)$ such that Assumption 5.2 holds; $\tilde{t}' < \frac{S_\tau U_S}{U_\pi - S_t U_\pi}$ at a particular τ. If $\tilde{t}(\tau)$ is such that at this same τ condition (5.38) is satisfied, then we know that

$$\frac{S_\tau U_S}{U_\pi - S_t U_\pi} > -\frac{S_\tau}{S_t}\left[1 + \frac{\psi'}{v'S_t}\right] \Rightarrow -\frac{\psi'}{v'S_t} < \frac{U_\pi}{U_\pi - S_t U_S}$$

By Lemma 5.4 $(U_\pi - S_t U_S \geq 0)$, we know that if $-\frac{\psi'}{v'S_t} < 1$, then $\hat{\tau} = \tau$. From Theorem 5.5, we know that one possible optimum incentive compatible contract has the property that Assumption 5.2 holds for all τ; thus, as long as $-\frac{\psi'}{v'S_t} < 1 \;\; \forall \tau$ the agent will state the true outcome of Research, τ, when τ is unobservable. **QED**

5.4 Summary

In Chapter 5 we have shown that an optimal ICDR R&D subcomponent contract can generally be arranged between a managing principal and a performance seeking agent. This is in contrast to Chapter 4, section 4.4, which indicated that no Theorem stating a similar general result could be attained with a profit seeking agent. More strongly still, in the absence of an observable Research outcome, optimal R&D production organization, based on the truthful revelation of the Research outcome by the agent, is possible under performance seeking agency but not under profit seeking agency. This is potentially a critical production organization consideration as knowing the outcome of Research allows the principal to concurrently balance the production of the other subcomponent inputs to the final good. These results do not suggest that a managing principal should organize all subcomponent production using performance seeking agents; merely that a managing principal should be aware of the characteristics of various possible agencies when it optimizes final good production organization.

Chapter 6: An Analytical Treatment of Mars Observer Production Organization

6.0 Segue from Theory to Observation

The Mars Observer experience described in Chapter 2 highlights R&D efforts characterized by subcomponent production, profit seeking and performance seeking agents, and issues of whether the outcome of Research is observable and the outcome of Development enforceable. In Chapters 3, 4, and 5 we examined theoretical R&D production organizations characterized by subcomponent production, profit and performance seeking agents, and the effects of observability and enforceability. The intent of Chapter 6 is to assess the production organization employed for the Mars Observer mission in light of the theoretical treatment. Before this assessment can be made, the applicability of the theory to the practice must be appropriately weighed.

The analytical approach has characterized optimal incentive compatible direct revelation (ICDR) contracts. There is no *a priori* reason to believe that contracts employed in practice will be ICDR contracts. The credibility of this analytical technique as a tool to assess actual production organization rests in an appeal to the Revelation Principle and in the validity of the model chosen as a representation of reality. We rely on the Revelation Principle (see section 4.0, page 30) to assure that there exists a correspondence between every contract employed in practice and an ICDR analog. We rely on the Revelation Principle and the validity of the model employed to assure us that the optimal ICDR contract characterized under the structure of the model is the analog of an optimal production organization employed in practice. Granting the applicability of the Revelation Principle, we must justify the use of the R&D production models of Chapters 4 and 5 as proper models of Mars Observer subcomponent production before we may legitimately assess the production organization decisions of the Mars Observer Project Office.

As initially structured, each Mars Observer subcomponent contract included a mechanism for specifying the final price and performance level after the initial research phase was concluded. For the experiments this mechanism was the margin allocation process. The potential physical resource consequences of the margin process led to the need for a means of modifying the price and performance of the spacecraft; thus, the unilateral modification process. To justify that our modeling applies to Mars Observer production it is critical to specify whether these mechanisms could (or should) have been part of a complete contingent contract or were parts of an optimal incomplete contracting process. Re-phrased, were the initial Mars Observer subcomponent contracts designed subject to renegotiation (incomplete) or were they structured for contingent re-contracting of price and performance given the outcome of a first production phase? The resolution of this question is not obvious, for whereas the margin allocation and unilateral modification processes were included in the initial contracting plans neither is explicitly specified as a contingent contract and the degree of implicit specification is, naturally, a matter of debate.

The models employed consider complete contracts over the two stage R&D production processes. The principal and agent agree to a specific Research investment, λ, and an explicit range of Development investments contingent on the outcome of the Research [$p(\tau)$ for the profits seeking and $t(\tau)$ for the performance seeking agent]. No renegotiation occurs, though the price and scope of the final product, S, are only known when the outcome of Research is announced. Optimal renegotiation between production stages has been theoretically justified by Tirole as a product of the principal not knowing his values *ex ante* for the probabilistic outcomes of agent investment during the first production stage -- perhaps because of the impacts of other concurrent procurements.[42] Our analysis internalizes the impacts of concurrent subcomponent procurements under the proxy of residual funds, Π, jointly valued with the production outcome in question, S.

[42]Jean Tirole, "Procurement and Renegotiation," *Journal of Political Economy*, vol. 94, no. 2, 1986, pages 235-259.

In so doing we remove the need for an incomplete contract as the principal is *ex ante* aware of the tradeoffs between subcomponents that he will value even though he is not aware of the specific trades he will have to make. If the Mars Observer Project Office was initially aware of its potential tradeoffs among the various subcomponents, then it should have been possible and desirable to fashion complete R&D contracts. From this theoretical perspective, the margin allocation and unilateral modification re-contracting processes should have been elements of complete optimal contracts; thus, there must be complete ICDR analogs of each.

Our approach to complete contracts specifically applies when all subcomponents to be purchased besides S are known commodities not undergoing R&D. However, in the Mars Observer experience, most of the subcomponents are demonstrably undergoing R&D production; thus, the applicability of our single R&D subcomponent model is a concern. We provide the following observations to mitigate this concern and rationalize the use of our model as a multiple R&D analysis tool for Mars Observer:

> If there are many subcomponents, all of which are contracted for via optimal ICDR contracts, then the mean outcome should be a reliable predictor. Thus, Π can be thought of as a proxy for the mean outcome against which optimal tradeoffs with S are determined.
>
> The novel subcomponent impacts identified by our model come about from the positive tradeoffs between S and Π; i.e. $U_{S\Pi} > 0$. If other subcomponents undergoing R&D were explicitly included and optimal contingent contracts determined for each, then the contracts would similarly be affected by cross partials between the subcomponents. Individual contracts under multi-subcomponent R&D production organization should be more complex yet have similar characteristics to the single component case.
>
> The necessary and sufficient conditions which determine and characterize each individual subcomponent contract would be dominated by the incentive compatibility constraints for the particular agent being contracted. Thus, each individual R&D contract might be very similar to the single subcomponent contracts modeled here.

A final concern over the applicability of our theory to Mars Observer rests on the juxtaposition of bilateral monopoly arrangements in practice with maximization relative to the principal's values in theory. The lack of transferable utility renders the standard approach of maximization of total surplus inappropriate. Some arbitrary weighting of returns between principal and agent would only complicate analysis without aiding in distinguishing the effects of profit from performance seeking agency which this research finds key and novel. Further, any *ex ante* arbitrary weighting of returns would remain subject to a post-Research, pre-Development participation constraint issue (the 'Hold-Up' problem). Therefore, we rely on an acceptably high reservation wage, κ, negotiated before the contract to account for all *ex ante* bilateral monopoly concerns.

For simplicity, the theoretical treatment did not include any interim participation constraints. Inclusion of such constraints would have complicated the analysis without substantively adding to the distinction between profit and performance seeking agency. The analysis implicitly assumes two means of persuading the agents to participate in the Development stage: the performance seeking agent's desire to participate until performance is attained and the profit seeking agent's desire not to loose his Research investment (recall that the profit seeker is reimbursed after final delivery).

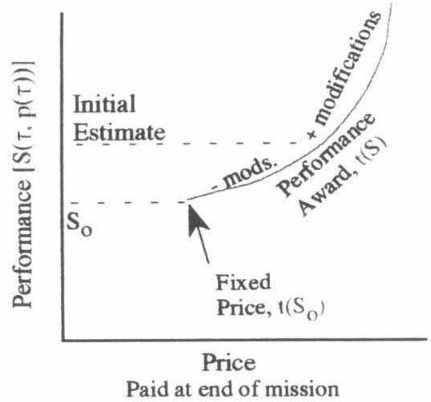
6.1 Characterization of the Original Bilateral Monopoly Contracts

If the initial subcomponent R&D contracts for Mars Observer were intended as complete contracts and we wish to assess their optimality, we must characterize them in a manner that affords comparison to the optimal ICDR analog to the optimal real contract. To do this the margin allocation and unilateral modification re-contracting processes must be accounted for along with clear identification of whether the contract relies on final performance (S) or the outcome of Research (τ) for the final price/performance decision.

As initially contracted, the spacecraft was to be produced in accordance with the design and fabrication practices of the contractor without oversight from the Project

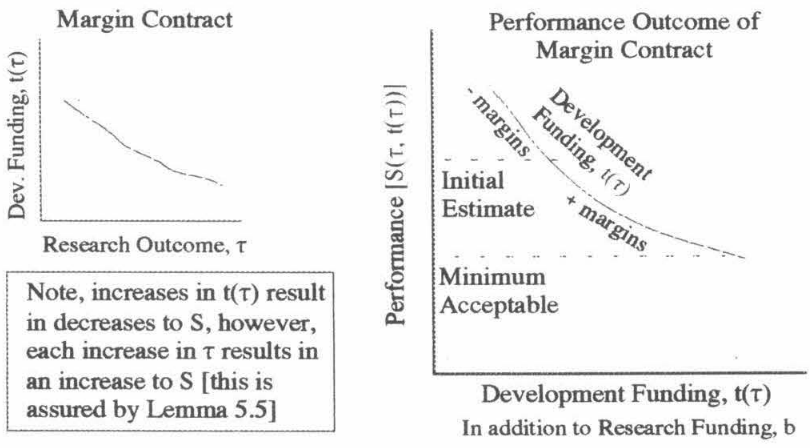
Office other than coordination assistance with the experiments; therefore, it is reasonable to assume that the outcome of spacecraft Research was not observable. By Theorem 4.3, an optimal ICDR R&D contract with a profit seeking agent and without an observable Research outcome must be based on the final outcome of production. The initial contract included a fixed price and a performance award that varied in the performance attained. Unilateral modifications were requests to trade price for performance relative to a technical tradeoff resulting from the prior Research investment. By Theorem 4.3, optimal Research investment would have to be enticed relative to final performance. Thus, Figure 6.1 incorporates the unilateral modification process into a variable performance award.

Figure 6.1: Initial Spacecraft Contract



Margin management implies a negative relationship between the outcome of Research, τ, and Development funding, $t(\tau)$, but in a manner such that each higher τ and lower $t(\tau)$ pair results in greater final performance, $S[\tau, t(\tau)]$. Figure 6.2 illustrates the general characteristics of such a contract in a manner appropriate for ICDR complete contracting. Theorems 5.5 and 5.6 state that optimal ICDR R&D contracts with performance seeking agents can be based on the outcome of Research whether the

Figure 6.2: Initial Experiment Contracts



outcome is observable or not and that Development funding may be decreasing in the outcome of Research. The appropriateness of Figure 6.2 to the actual experiment contracting process rests on whether the functionality required for a complete contract was implicit between the Project Office and each experiment agent, for no explicit functionality existed in any of the initial agreements.

6.2 Impacts of Different Experiment Agent Types

The description of the Mars Observer experience has proceeded under the presumption that there existed a motivational difference between the experiment agents that were planetary scientists and those that were institutional representatives of a JPL *Division* or NASA Center. Both types of Agent are assumed to be motivated by the performance capability of their experiments; however, the JPL or NASA agent is assumed to have a greater relative motive to employ funds toward non-performance ends.

When the outcome of Research is observable and the final outcome of their experiment enforceable by the principal, the only possible effect on production from performance motivated agents with different non-performance motives is through the agents' investment in Research (λ in Chapter 5) and the principal's decision on allocating Research funding (b in Chapter 5). An agent more motivated by the non-performance use of funding will allocate more of the Research funding to these other uses, and, therefore, proportionately less to Research investment than will an agent more motivated by performance (e.g., $b-\lambda$ will be greater for a NASA agent than for a Scientist agent).

6.3 The Lack of Observables in Experiment Subcomponent Production

Recall from Chapter 2 that no engineering models or breadboards were approved for any of the instruments. Thus, the Research on the novel techniques and processes employed for each instrument would have to be conducted in conjunction with the design and construction of the production unit. The effect of such a blurred Research and

Development process on the presence, timing, and meaning of observables is significant. The margin contract relies on reports of progress to determine insurance allocations from the margin fund pool. An observable that is dependably correlated with expected performance is an appropriate means of managing such contracts -- the observable becomes the progress report. The absence of a clear observable introduces the need to ask the agent for a progress report which the principal cannot verify independently. Granting that each of the initial experiment agents had some fundamental interest in the performance of his instrument, the model of Chapter 5 applies and the discussion of Section 5.3 on the role of the observable is pertinent. The optimal ICDR contract must include the truthful revelation of the Research outcome by the agent. This non-observability requirement will tend to make the slope of the contract steeper.

6.4 The Potential Lack of Enforcement in Experiment Subcomponent Production

Two of the possible types of instrument agents 'out rank' the Project Office: A JPL Divisional Agent and a NASA Center Agent.[43] The authority of the Project Office over these two types of agents may not be substantial. This diminution of authority raises the possibility that the Project Office could not credibly threaten to punish the agent should the outcome of Development be an experiment less capable than that which would result given the outcome of Research and the Development funding provided to the agent by the Project Office. As with the diversion of Research funding into non-Research uses, an agent not subject to enforcement may divert Development funding into non-Development uses. Therefore contracting with such agents must account for whether the Project Office is capable of enforcing the outcome of Development. Initially granting the same margin contacts to Scientist agents and non-enforceable NASA and JPL agents decreases the likelihood that the initial contracting was optimal.

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[43]see Figure 2.2, page 5.

6.5 Renegotiation as a Response to Agency Problems

If subcomponent production is optimally organized via complete contracts, then incidences of renegotiation imply a recognition of sub-optimal initial production organization. For Mars Observer, subcomponent renegotiation took the form of a change in agent (either through elimination or replacement), a change in the observability of the Research outcome, a change in the enforceability of the final outcome, and/or a change of contract form. Table 6.1 illustrates these changes. Analyses of the reasons for and outcomes of contract renegotiation indicates whether the Project Office recognized sub-optimal initial contracting and whether such recognition was accompanied by a change that addressed the cause of the sub-optimality, resulting in a 'more optimal' process.

Table 6.1: Contract Renegotiation

Subcomponent	Initial Contract Characteristics			Change in Contract Form?
	Agent Type	Observability	Enforceability	
Spacecraft	Profit	No	Yes	Yes
~~Map. Spec.~~	Deleted ~~JPL Div.~~	Deleted ~~No~~	~~No~~ Deleted	~~N/A~~
Atm. Sounding	JPL Div.	No	No	No
Gamma Spec.	NASA	No	No	No
Altimetry	NASA	No	No	Yes

(shaded) = Renegotiated

JPL Divisional Agent: Mapping Spectrometry Renegotiation

Any observability and enforcement problems surrounding the Mapping Spectrometry contract were dealt with in a summary fashion when the experiment was eliminated from the mission. There is no post-renegotiation evidence to corroborate the suggestion that the initial contract poorly accounted for JPL Divisional agency problems resulting from the lack of observables and enforcement. Thus, though wonderfully absolute, the motives for this renegotiation are ambiguous.

JPL Divisional Agent: Atmospheric Sounding Renegotiation

The atmospheric sounding experiment was the other experiment initially contracted to a JPL Division. As described in Chapter 2, there is substantial evidence that the Project Office believed that the margin allocations to this instrument were excessive and the Project Office had difficulty obtaining the authority to redirect the effort. Eventually, the resource drain from the Project to the JPL Divisional Agent was so severe that the instrument was 'projectized' -- authority over its development was transferred from the JPL Division to the Project Office. This could be seen as a move to establish credible enforcement and to enhance observability. However, the renegotiation had been delayed far too long by JPL authorities above the Project Office to save much. Thus, it was perhaps more a punishment than an act designed to attain some vestige of optimal subcomponent production.

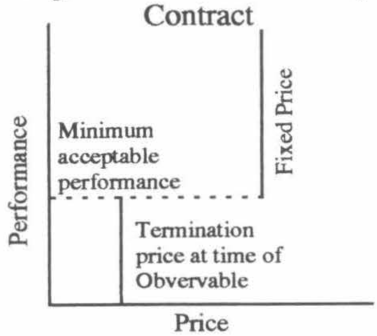
NASA Center Agent: Gamma Ray Spectrometry Renegotiation

The Project Office was seriously concerned with the responsiveness and accountability of the management of the gamma ray spectrometry experiment at NASA's Goddard Space Flight Center. After substantial margin allocations, and much complaining by the Project Office, management authority at Goddard for this experiment was transferred to a different subsection. Enforceability could not have been affected by this internal Goddard change as the agent still 'out-ranked' the Project Office and there was no tangible increase to observability. The only positive result of this renegotiation was a possible shift in agent motivation away from non-performance uses of funding toward performance uses. Thus, the Project Office would know that less of the funding provided would be wasted but it would not know what level of performance it was purchasing until the instrument was delivered and operational.

NASA Center Agent: Altimetry

The initial altimetry experiment, a radar altimeter, was eliminated due to escalating price and physical resource estimates. Unlike the mapping spectrometry experiment, altimetry was not dropped from the mission -- a different altimeter was selected. The laser altimetry experiment was still under the authority of Goddard; however, the contracting arrangement was altered. Rather than retaining the standard margin approach, a discontinuous contract was employed, illustrated by figure 6.3. Over a broad range of expected performance, the contract was fixed price. If any observable indicated expected performance below a contractually pre-determined level, the effort would be terminated.

Figure 6.3: New Altimetry Contract



This renegotiation did not alter the hierarchical conditions that had led to the lack of Project Office enforcement. However, the use of a fixed price contract, combined with the retention of an Agent with some fundamental interest in altimeter capability, can be seen as an attempt to obviate both observability and enforcement concerns. When asked to reveal a credible example of Research progress, the Agent would have no incentive to present something below the minimum acceptable if progress above minimum had been attained. Further, no incentive was present to misrepresent performance above the minimum acceptable level.

Instrument Renegotiation and Observability

Given Research outcomes that are observable by the Principal, and Development outcomes that are enforceable by the Principal, the analysis of Chapter 5 suggests that optimal, incentive compatible experiment contracting is readily attainable with experiment agents who are motivated by the performance capabilities of their experiments. However, if the outcomes of Research can be concealed from the principal, the agent may wish to misrepresent its Research outcome in order to obtain additional funding that it may use for non-performance desires. The agent can do this if the funding received from the principal in response to the misrepresented Research outcome is sufficient to deliver the level of experiment capability attendant to the funding received. The potential misrepresentation of the Research outcome will be termed an interim adverse selection issue, that, if injected into the Principal's production organization problem, can seriously affect the potential of optimal, incentive compatible R&D contracts.

Based on the analysis leading to equation (5.38) in Section 5.3, different performance seeking experiment agent types will reveal or conceal their Research outcome depending on the sensitivity of their Development funding contract [$t(\tau)$ in Figure 6.2] to the Research outcome. We know from Lemma 5.5, that the Development contract will assuredly provide for more performance with each increasing revelation of the Research outcome; thus, the agent will obtain utility from revealing the true outcome. However, if the Research outcome is not observable, the agent will forgo utility from other uses of Development funding if it reveals the true outcome. Thus the result in equation (5.38) is intuitive and can be restated as:

> If the incremental change in Development funding at the particular Research outcome exceeds a relationship that is increasing in the ratio of the Agent's marginal disutility of revelation to its marginal utility of revelation, then the agent will reveal the Research outcome.

The distinction among the experiment agents is their valuation of non-R&D uses of funding; thus, under the same contract and outcome, some agents may reveal the true outcome of Research and some may not, with NASA Center and JPL Divisional agents more likely to misrepresent then Scientist agents.

As noted, Mars Observer experiment production lacked clear observables. If the Project Office encountered problems due to interim adverse selection resulting from the lack of observables, then an expected response (assuming the Project Office sensed the cause of the problem) would be to generally increase the slope of the Development contract for that experiment through project initiated renegotiation. To give the agent an incentive to respond to the new contract, it is reasonable to assume that the contract would require an increase in the average level of funding. [Referring to Figure 6.2, the suggested re-contracting for the same range of performance outcomes would be to increase the slope and also to raise the general level of $t(\tau)$.]

Enforceability concerns were effectively dealt with in the re-contracting of the Altimetry and Atmospheric Sounding experiments. Observability, however, remained a concern; thus, interim adverse selection concerns were pertinent. Altimetry renegotiation represents a dramatic increasing of the Development contract slope relative to the initial Altimetry contract; however, as both price and performance expectations were lowered by replacing a complex and highly capable radar-based design with a laser-based design it is difficult to perceive Project Office reaction to interim adverse selection concerns. Atmospheric sounding renegotiation offers clearer indications of the Project Office responding to interim adverse selection concerns. The minimum acceptable level of performance was reduced, the acknowledged price raised, and the access to margins reduced (the slope increased by making it less negative).

The renegotiation of the Gamma Ray Spectrometry experiment did not secure enforceability as the experiment remained under the control of a NASA Center. If the re-contracting had secured observability, then the agent's non-performance use of Development funding would be discernible, and, thus, a margin development contract could have been used. However, if observability were not secured, then the Gamma Ray Spectrometry Agent was free to claim as large a margin allocation as he inferred he could without having to claim a Research outcome so low as to risk termination of the experiment.

The two Scientist Agent experiments, Thermal Emission Spectrometry and Imaging did not undergo any substantial renegotiation as characterized in Table 6.1. An attempt was made to fund an Engineering Model for the Thermal Emission Spectrometry experiment; however, the Project Office opted not to fund this potential observable. These actions are not inconsistent with the statement that the Project Office considered there to be no serious sub-optimality problems with the Scientist Agent subcomponents.

Repercussions of Experiment Contracting on Spacecraft Contracting

Any experiment margin contracting approach, whether optimal or not, faces the prospect of impacting spacecraft production as the increased physical resource requirements attendant to margin allocations are demanded from the spacecraft. Once spacecraft Research had concluded and the technology level was established, producing more physical resources is a matter of allocating more money to Development. In the case of the Mars Observer spacecraft contract, the Unilateral Modification was the mechanism used to organize the Development production of increased instrument resources. An assessment of this process with reference to the analysis of Chapter 4 is enlightening.

When the Project Office contracted for a spacecraft for the Mars Observer mission, the product desired was dependable experiment resource services for at least two years in Mars orbit. The specific amount of resources was not knowable at the start given the uncertain needs of the instruments. Thus, the price/performance technological capability of the spacecraft was a significant issue subject to optimal R&D subcomponent contracting. This technology level would not be observable to the Project Office due to the nature of the product being procured: the extent of design studies and tests, the fabrication processes, the quality of labor, and many other inputs to production critical for reliability (expected performance at Mars) are not readily observable. However, it is in the interest of the Project Office that the Agent pursue technological improvements compatible with Project Office interest in expected performance. By Theorem 4.3 this can only be done with an incentive compatible R&D subcomponent contract based on the performance outcome of Development (as in Section 4.2). The contract illustrated in

Figure 6.1 has the positively monotonic property which, by the analysis of section 4.2, could have represented a necessary and sufficient condition for an optimum contract between the Project Office and the spacecraft contractor. It is not obvious or perhaps even knowable whether the initial contract was sufficiently steep. However, the likely effect of re-contracting via the Unilateral Modification process can be posited relative to this condition.

When the Project Office requested an increase in experiment resources via a unilateral modification, it was requesting a trade of price incurred for performance received relative to a production possibilities frontier based on the technology outcome of spacecraft Research. Regardless of the questionable mechanism employed to arrive at a price for the modification, the salient optimal incentive compatibility issue is that the price of the requested increase to the R&D efforts was added to the fixed price segment of the contract, not to the performance award. In practice, the performance award was the truly fixed aspect of the contract with the initial 'fixed' price varying with the requested performance increases. This type of contract does not correspond to the ICDR contract illustrated in Figure 6.1 and bears no resemblance to a contract that would have enticed optimal Research investment.

The historical evidence suggests that the Project Office had become concerned that the spacecraft technological investment had been insufficient. The Project Office renegotiated the spacecraft contract by internalizing many of the reliability oriented functions and increasing monitoring of the spacecraft agent by insisting that JPL practices be used under JPL supervision. At no time, however, did the Project Office increase the performance award instead of internalizing functions.

6.6 Appropriate Production Organization for Different Circumstances

What follows are synopses of the types of R&D contacts that can reasonably be justified under different agent and information environment circumstances. These synopses are drawn from the Mars Observer pathology, the analysis of Chapters 4 and 5, and the preceding sections of Chapter 6. Table 6.2 accompanies the discussion as a summation.

Pure Profit Seeking Agent

I. Never employ a pure fixed price R&D contract, the agent will merely claim a very bad Research outcome and produce at the 'off-the-shelf' technology level [see section 4.2, the Caveat for contracting Case A].

II. If the outcome of Research is observable, then Section 4.4 suggests that, although a wide range of contacts may be possible, contracts that are strictly positive in the observable are certainly appropriate. A Fixed Price Performance Award contract based on the outcome of Research can be the analog of an optimal ICDR R&D contract for these circumstances.

III. If the outcome of Research is not observable, then Theorem 4.3 states that the contract must depend on the final outcome of R&D production rather than on a reported interim outcome. As illustrated in Figure 6.1, the Fixed Price Performance Award contract can be the analog of an optimal ICDR R&D contract for these circumstances.

IV. If the outcome of Development is not enforceable, then do not contract with a pure profit seeking agent.

Performance Seeking Agent

I. If the outcome of Research is observable, then employ the performance seeking agent most interested in performance and least interested in other uses of funding (e.g., low $\psi'/v'S_t$). For these characteristics, some form of partial margin contract may well be the analog of an optimal ICDR contract.[44]

II. If the outcome of Research is not observable, then the conclusion is the same as in (I). By Theorem 5.6 contracting without an observable outcome of Research may be critically affected by the particular performance seeking agent in question. The optimal ICDR contract may need to be steeper (more positive, less negative) in the stated Research outcome than for the observable case.

[44] An agent with greater interest in other uses of funding may nonetheless be the best choice if the agent uniquely possesses fixed assets that would lower the required Research investment, λ,. This is a possible justification for contracting a NASA Center or JPL Division rather than a Scientist agent; however, the comparative contracting decision must consider the costly effects of non-enforceability.

III. If the outcome of Research is observable but the outcome of Development is not enforceable, then the conclusion is the same as in (I). In this case, the agent will utilize a calculable part of his Development funding in non-performance pursuits.

IV. If the outcome of Development is not enforceable and the outcome of Research not observable, then the optimization problem cannot result in a contract that varies in the stated outcome of Research; thus, a fixed price contract, such as the renegotiated altimetry contract, is the optimal ICDR R&D contract.

Table 6.2: Actual Contracts that may Correspond to Optimal ICDR R&D Contracts

Agent Type	Production and Authority Characteristics			
	Observable and Enforceable	Non-Observable and Enforceable	Observable and Non-Enforceable	Non-Observable and Non-Enforceable
Profit Seeking	Fixed Price/ Performance Award based on the Research Outcome	Fixed Price/ Performance Award based on the Development Outcome	Do not Contract	Do not Contract
Performance Seeking	Margin Contract based on the Research Outcome	Margin Contract based on the stated Research Outcome*	Margin Contract based on the Research Outcome**	Fixed Price

* By the analysis of Section 5.3 that leads to Theorem 5.6, such a margin contact may be steeper than when the outcome of Research is observable.
** The optimal contract in this case must be determined under the realization that some of the Development funding will be used for non-performance purposes. The suggestion that this contract is optimal is based on an extension of the analysis contained in Chapters 2-6, this case is not dealt with in the theory nor does it arise in the Mars Observer history.

6.7 Summary

There is no evidence that the Project Office initially contracted or renegotiated with a clear recognition of agency effects on the potential of organizing Mars Observer subcomponent production optimally. In particular, non-enforceable margin R&D contracts to four NASA Center and JPL Division agents plus the completely backward incentives of the spacecraft unilateral modification process are demonstrably non-optimal approaches to R&D production organization. The numerous acts of renegotiation suggest that the Project office recognized that there were problems with the initial set of contracts. However, recognition that a problem exists does not imply realization of the root cause or optimal cure. The altimetry and atmospheric sounding experiments appear to have been renegotiated in the direction of optimality; however, the gamma ray spectrometry and spacecraft renegotiations did not move toward optimality. The Mars Observer production organization was sub-optimal due to neglect of agency issues, primarily moral hazard.

Chapter 7: Examples of Various R&D Production Organizations

7.0 The Cassini Resource Management Plan

The Cassini mission to Saturn is currently undertaking a similar R&D process to that of Mars Observer. Initiated in 1986, the project has experienced several major programmatic changes after many major subcomponent suppliers were selected; thus, conditions of bilateral monopoly exist between the Cassini Project Office and its agents.

Among the thirteen major Cassini subcomponent suppliers, seven are JPL Divisional or NASA Center agents, three are foreign funded, three are scientists at American universities, and none is purely profit seeking.[45] Given that the preponderance of agents 'out rank' the Project Office (or, in the case of the foreign agents, are not bound to the Project Office for funding), substantial enforcement problems pertain. Additionally, the long transit (seven years, arriving at Saturn in 2004) so delays the time when enforcement would occur that the threat of enforcement may not be significant. Further complicating production organization, subcomponent production is distributed widely, making the tenuous goal of observability all the more tenuous.

Optimal R&D subcontracting to performance seeking agents with neither credible enforcement nor observability of the Research outcome is limited to fixed price contracts.[46] Interestingly, in 1991 the Cassini Project Office adopted a resource management plan in which each of the thirteen agents was given fixed allocations of funding and physical resources. Each agent is to pursue the best performance/resource tradeoff that they can. Taking advantage of the multi-input performance production functions, the agents are allowed to barter funding and physical resources among themselves. The Project Office will not augment the total endowments of funding and

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[45]The spacecraft and six of the experiments are contracted to JPL Divisional or NASA Center Agents, three experiments (one a Titan probe) are contracted to foreign Agents, and three of the experiments are contracted to scientist Agents from American universities.

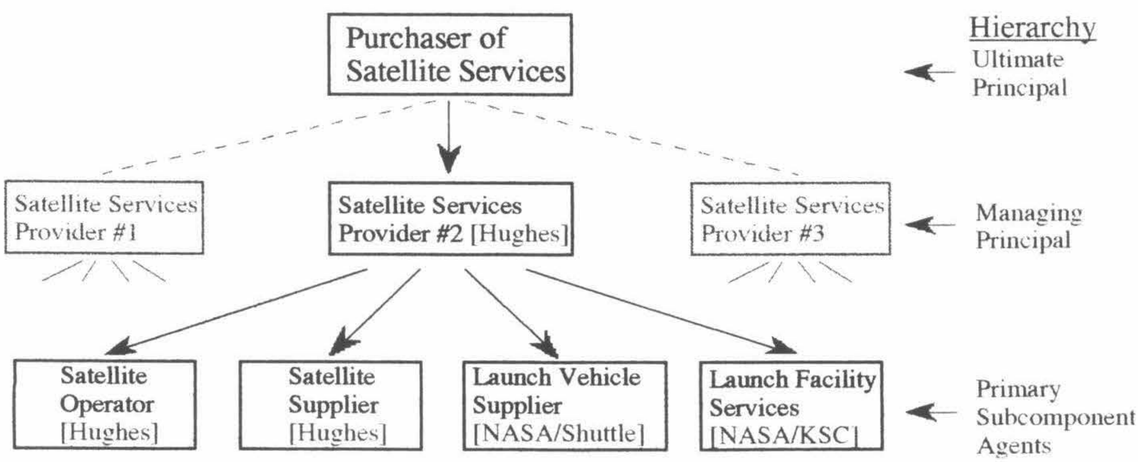
[46]See section 6.6.

physical resources to the group of agents such as is the case under margin management. In essence, a multi-member, multi-dimensional, and multi-period Edgeworth box endowment economy has been initiated. Thus, the organization of subcomponent production chosen by the Cassini Managing Principal appears consistent with the recommendations of optimal R&D theory.

7.1 The Procurement of Booster Engines for Commercial Satellite Services

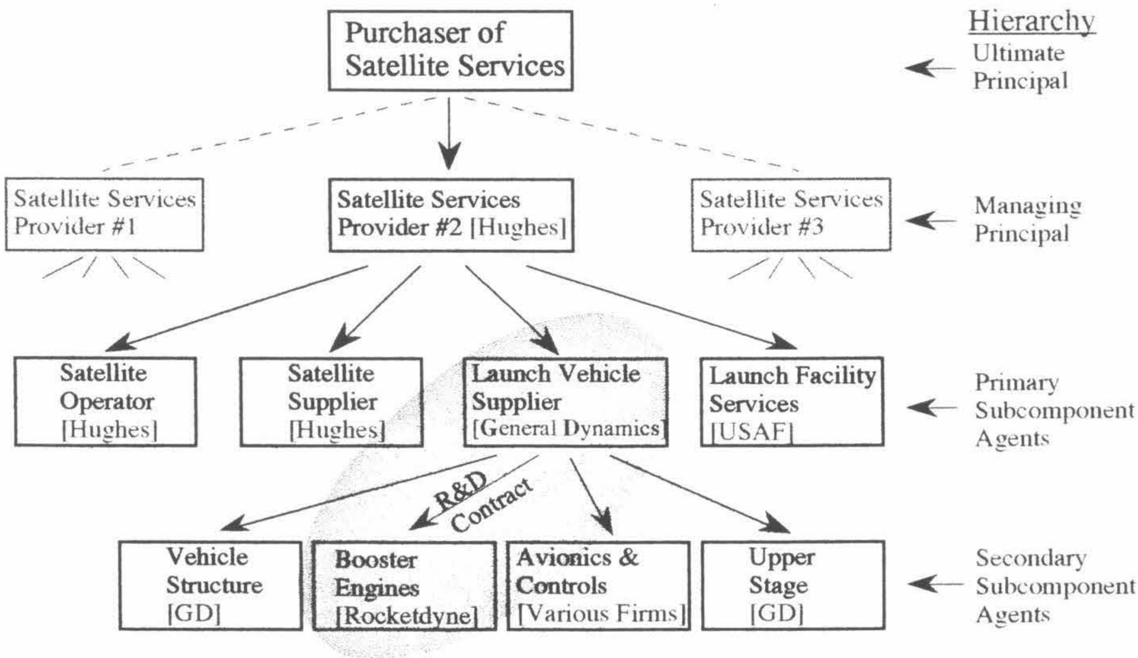
The commercial procurement of satellite services involves an authority hierarchy from Ultimate Principal to Subcomponent Agents that is similar to the hierarchy for the procurement of a planetary science mission. Figure 7.1 illustrates an example authority hierarchy for satellite services that existed before the Challenger Shuttle disaster. Procurement along one possible Managing Principal path is shown. Over time, each subcomponent procurement could be subject to R&D. Prior to Challenger, the choice of subcomponent suppliers was constrained by the Boland Amendment which mandated a Shuttle monopoly for American launch services. As such, contractual terms for Launch vehicle and facility services were dictated to the Managing Principal; thus, examination of the subcomponent 'contracts' may not be particularly relevant to a general assessment of R&D contracting.

Figure 7.1: Pre-Challenger Procurement of Satellite Services



Examination of subcomponent procurement may, however, be relevant to a general assessment of R&D procurement after Challenger. With the Shuttle fleet grounded, high costs and low reliability exposed, and a backlog of satellites awaiting launch, a number of commercial launch vehicle companies were formed. Figure 7.2 illustrates the changes to the satellite services procurement hierarchy post-Challenger with the addition of a secondary tier of subcomponent suppliers beneath the launch vehicle supplier. A particular launch vehicle supplier, General Dynamics, is noted. General Dynamics was one of several firms wishing to capitalize on the commercial launch service opportunity by restarting production of a pre-Shuttle launch vehicle, the Atlas booster. No Atlas hardware had been manufactured for over 20 years; thus, updating Atlas subcomponents (R&D) would be a pertinent concern for General Dynamics. The booster engine production contract is highlighted as it involved R&D.

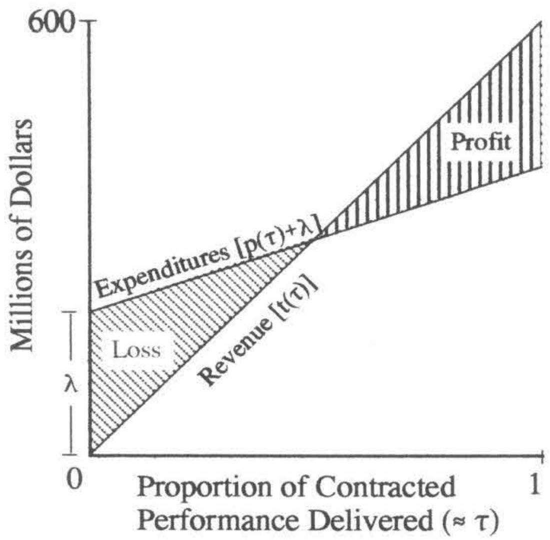
Figure 7.2: Post-Challenger Procurement of Satellite Services



Given that General Dynamics was committed to restarting Atlas production, there was only one realistic choice of engine manufacturer, the Rocketdyne division of

Rockwell International, which was the past manufacturer of Atlas engines. General Dynamics and Rocketdyne entered into a contact for 60 Atlas engine sets at a price of approximately $600 million. The entire price is not paid to Rocketdyne 'up-front'. Instead, Rocketdyne receives a payment for each engine set delivered. Should Rocketdyne's engines prove unreliable, Rocketdyne may never be able to deliver all 60 engines either due to lack of customers for Atlas launch or due to General Dynamics termination of the Rocketdyne contact with an accompanying suit for reliance damages. Figure 7.3 illustrates the essentials of this monopoly, R&D contract between a profit seeking agent and a Principal who values a balance of performance from numerous subcomponents. Due to the reliability arguments, there should be a direct relationship between the degree of valued technological innovation claimed by Rocketdyne and the proportion of the 60 contracted engine sets that are delivered and perform adequately.

Figure 7.3: Booster Engine R&D Contract



The Atlas engine contract specifies a number of upgrades to the old engines. Beyond simple performance improvements (thrust, efficiency, mass), numerous production process improvements meant to insure reliable performance are specified. Whereas raw measures of performance may be observable each flight, myriad production processes may not be observable; further, their impact on reliable performance may not be discernible until after many launches. General Dynamic's decisions regarding production of the other launch vehicle subcomponents and appropriate insurance coverage would have benefited substantially from knowledge of the true extent of the engine improvements. Thus, it is not surprising that the contract includes technological innovations by Rocketdyne to the Atlas engine even though many of these innovations were not directly observable to General Dynamics.

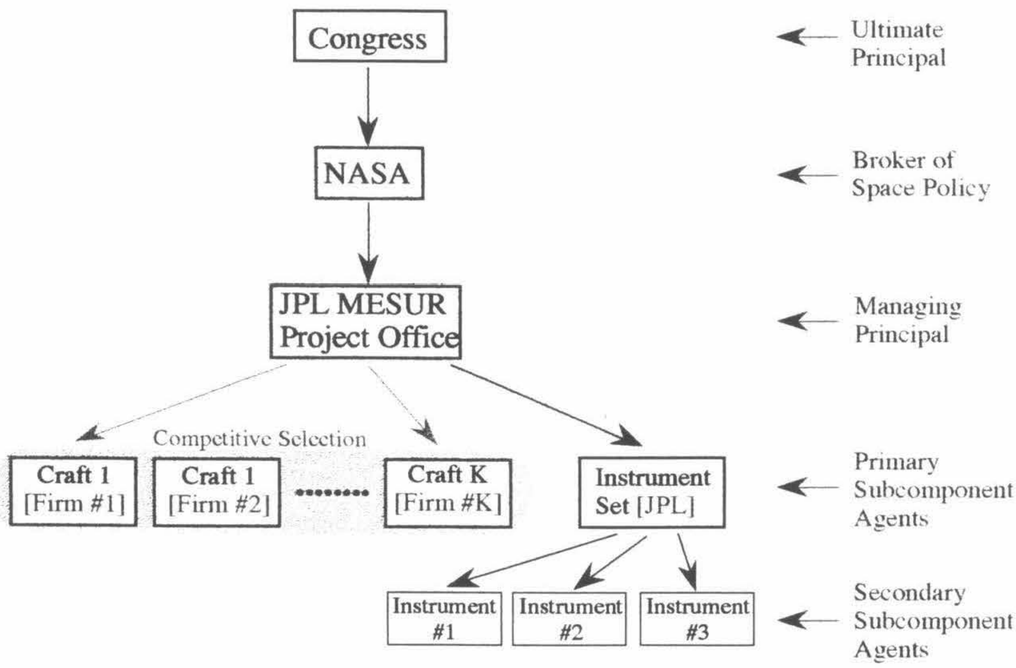
The lack of observability over the outcome of Research performed by a profit seeking agent implies, by Theorem 4.3, that the optimal R&D contact may only be conditioned on the outcome of Development (the case of section 4.2). Thus, the Atlas engine contract should either be based on the observed performance of each engine [which Figure 7.3 surly does] or somehow utilize the repeated game nature of multi-unit production to make the outcome of Research effectively observable. An argument can be posed that the true outcome of Research can be estimated accurately over the observed unit-to-unit performance as the number of units launched increases. This should result in a credible threat deterring Rocketdyne from misrepresenting the outcome of Research too severely. Rocketdyne's misrepresentation calculus would surely be affected by the potential unit-to-unit profit represented by each engine use. Thus, it can be supposed that a contract such as that illustrated in Figure 7.3 can be 'steep enough' over N-sufficiently large units that the agent will truthfully reveal the outcome of Research.

7.2 Procurement of the Mars Environmental Survey: A Suggested Approach

The Mars Environmental Survey (MESUR) is currently under consideration as the American planetary science mission to Mars after Mars Observer. MESUR is to consist of several landed craft conducting uniform measurements at numerous points on the Martian surface. The landed packages consist of two major subcomponents: a craft that provides transit, landing, communication, and power services; and an instrumentation set designed to make the required measurements. Clearly there is a connection between the two subcomponents since the instrumentation set cannot require larger mass, power, and communication resources than the craft is capable of providing.

What follows is a proposal for procuring the MESUR mission in a manner corresponding to the general framework and recommendations of our analysis.[47] Figure 7.4 illustrates a suggested production hierarchy for MESUR Unlike prior hierarchies examined in this research, a competitive selection process is present; namely, the selection of the private firm providing the craft subcomponent.

Figure 7.4: Suggested Production Organization for MESUR



Craft Subcomponent -- Agency Concerns/Solutions

Table 7.1 provides an overview of the major agency concerns associated with procurement of the craft subcomponent of the MESUR mission and the suggested contractual solutions for each. Note that both initial and interim adverse selection

[47]Charles Polk, *Incentive Contracting for the MESUR Mission: Pathfinder and Network*, JPL Briefing to the MESUR Advisory Panel, April 4, 1992.

concerns are dealt with due to the opportunity to solicit competition among prospective agents. In the next two subsections, the complete contractual process will be described followed by an explanation of the properties projected to solve the agency concerns.

Table 7.1: Craft Agency Concerns and Solutions

Agency Concern	Contractual Solution
Selection of the agent most capable of undertaking an R&D production process that results in a mix of performance and price in accordance with Project Office values.	Auction process where bids are two dimensional: price and performance. The two top bidders are granted the right to participate in a 'Fly-Off'.
Moral Hazard concern that the outcome of Research will not truthfully indicate the investment in Research.	Per Chapter 4, the overall contract will be positive in the outcome of Research.
Interim Adverse Selection concern that the outcome of Research will not be observed and may not be truthfully reported.	The likelihood of winning the 'fly-off' and expected profits depend on an observable directly related to the Research outcome.

Craft Subcomponent -- Use of a 'Fly-Off' to Select Agent

Let **N** = the number of craft to be built and set to Mars and refer to the envelope of physical resources available to the instrumentation set as **E**. Before any selection information is requested from the prospective Craft Agents, the Project Office announces the following selection process:

i. The target **E** and **N** desired by the Project Office

ii. Selection of two prospective Agents in accordance with an auction based on the bid matrix of Figure 7.5. All prospective agents may bid among the 21 allowable combinations of Craft unit price and unit warranty. Figure 7.5 is configured to represent the valuations of the Project Office favoring balance between price and expected performance. The auction is an open English auction. Once bid, a cell cannot be bid by another participant. Participants may bid more than one cell. The two prospective Craft Agents who bid the two highest ranked cells will be granted the right to participate in a 'fly-off', in which each of the two will build, launch, land and operate one craft. The winner of the 'fly-off' will receive the contract for all **N** craft. If fewer than three bidders participate, the Project Office iterates the auction with different combination of **E**, **N**, unit prices, and warranties.

Figure 7.5: Craft Auction Matrix
#s in Cells Represent JPL Rankings

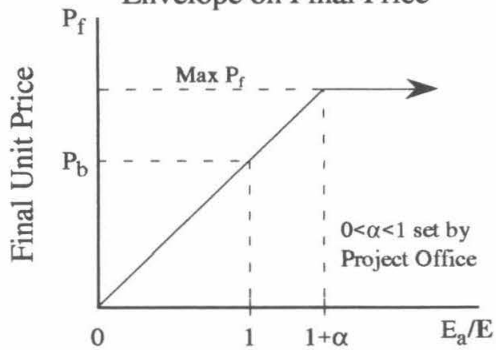
Warranty per Unit (% of Final Unit Price, P_f)	50	55	60	65	70	75
70%	1	2	4	7	11	16
60%	3	5	8	12	17	
50%	6	9	13	18		
40%	10	14	19			
30%	15	20				
20%	21					

Shaded cells: Not Offered for Bid

Bid Unit Price, P_b
Millions of $

iii. Before the fly-off launch, each of the two actual instrument set resource envelopes, E_a, is observed. Prospective final unit prices, P_f, are now known due to a relationship specified by the Project Office pre-auction that is exemplified by Figure 7.6 [by Figure 7.5, prospective warranties are also specified].

Figure 7.6: Effect of Actual Envelope on Final Price



Actual vs Target Envelope

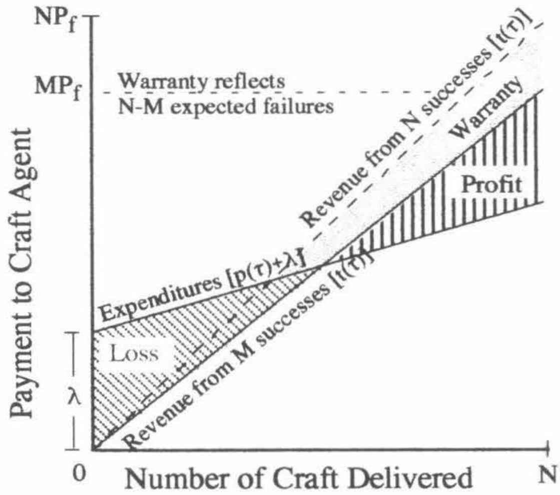
iv. Assuming that each 'fly-off' craft operates for two months on the Martian surface, then the winner will be the craft Agent with the highest E_a up to $(1+\alpha)$**E**, with a tie breaker on the size of the warranty.

v. If one craft fails to operate for two months, the other Agent wins.

vi. If neither craft operates for two months, revert to (iv)

vii The production contract form to be awarded to the fly-off winner is specified pre-auction and is exemplified by Figure 7.7.

Figure 7.7: MESUR Craft Contract



Craft Subcomponent -- Disposition of Agency Concerns by Contracting Process

Define the outcome of Research to be technology measured by its effect on the ability of the principal to convert funds into expected E_a, where expected E_a is the likelihood that E_a will last for the contractual duration of the mission and result in a payment of P_f to the agent. An increase in E_a that is due to a good Research outcome will decrease exposure to warranty claims and increase revenue due to its effect on P_f, whereas, an increase in E_a that is due to an input of more production funding but no better Research outcome will decrease profits. Therefore, the agent with the better Research outcome has an incentive to produce a proportionately higher E_a. Further, expected profits include the probability that an Agent is selected. The higher is E_a, the greater is the chance of winning both directly and because of the increase to the warranty tie breaker (see selection rule *iv* above). Thus, the higher is τ, the greater profit can be attained from increasing E_a. Therefore, E_a is an unambiguous signal of τ -- The higher is E_a, the more successful was the Agent's R&D outcome.

Competition to win the Fly-Off will alleviate the principal's concern over the truthful revelation of E_a and the Research outcome; thus, eliminating the interim adverse selection concern that, by Theorem 4.3, would otherwise render an optimal R&D contract based on τ impossible. The contract represented in Figure 7.7 provides for expected net revenues to be positively increasing for all Research outcomes; fulfilling the sufficient condition for an optimum to the agent's incentive compatibility problem. Therefore, the moral hazard concern over revealing truthful information regarding Research investment is alleviated. Our theory has not considered initial adverse selection among several agents, a concern which should be considered in suggesting that a procurement approach is optimal. In our suggested MESUR procurement approach, we posit that the initial adverse selection concern can be alleviated through the competition of an English

Auction which results in two 'winners' who go on to compete in the Fly-Off. Assuming that the initial bidders vary in their abilities to conduct the R&D production appropriate for MESUR and that the bidders have consistent priors over industry capabilities, then it is surely plausible that the proposed auction will result in the selection of the two Fly-Off contenders with the best comparative advantages relative to the principal's valuation of price and performance.

Production Organization of Instrument Set Subcomponent

As before, we assume that the Managing Principal, the MESUR Project Office, values a balance of mission performance and mission price. The contracting structure proposed for the craft subcomponent does not contradict this assumption in that increases in P_f are expected to result in increases in the quantity and quality (reliability) of E_a. However, E_a is not the performance that the Project Office values; rather, E_a is an input to the instrument set subcomponent production process that is intended to produce the Science measurement performance valued by the Project Office.

Depending on the types of experiment agents, nature of observability, and presence or lack of enforcement, the Project Office might optimally organize production of the instrument set subcomponent in any of the ways outlined in Section 6.6. Any contracting arrangement must include the reservation that no more physical resources can be used than can be accommodated by E_a. Thus, an optimal margin contacting arrangement with several scientist agents may well fix the physical resources that can be used yet vary the funding in negative proportion to the outcomes of each agent's Research.

In addition to the potential optimality of a margin or insurance type production organization for each element in the instrument set subcomponent, there is the potential optimality of an externally induced margin organization for the whole instrument set subcomponent. The instrument production functions can be assumed to be positively influenced by both physical resources (E_a) and funds; thus, increases in E_a above **E** may cause the Project Office to allocate fewer funds to the whole instrument set subcomponent. This externally induced margin production organization might be incorporated into the instrument Agent contracts in an incentive compatible fashion if the individual instrument tradeoffs between physical resources and performance and/or funding are sufficient to result in greater performance and/or profit.

Chapter 8: The Placement of R&D Procurement in Production Organization

The two fundamental issues dealt with in this thesis are the two fundamental issues of production: the division of labor and technological innovation. Technological innovation may be seen as entering production through the labor most adept at such innovation; or an entity adept at an innovation may be seen as self-selecting a place in production that maximizes its returns. Production is incremental and innovations enter production incrementally. The increments to production (subcomponents) are innovated by agents to the principal who purchases the final, assembled good. Some intermediate entity, the Managing Principal, will organize subcomponent production. In competition, the Managing Principal that best coordinates the motivations of the Ultimate Principal *with* the motivations of the subcomponent agents will succeed. Over time, this coordination must account for changes affecting the optimal organization of subcomponent R&D.

It is completely reasonable that optimal institutional coordination between the Managing Principal and the Subcomponent Agent will vary from final good to final good, from subcomponent to subcomponent, and from incidence of innovation to incidence of innovation. It is implicit that agency concerns will affect whether subcomponent R&D is conducted within the institutional boundaries of the Managing Principal or between legally distinct institutions. All the same, agency concerns pertain. The agent of Chapter 5, partially motivated by subcomponent performance, partially by other uses of funding, can be seen as representing either an agent internal to a Managing Principal's institution or an external agent with strong repeated game or post-game concerns. The agent of Chapter 4 is a classic one shot profit maximizer. As we have seen, optimal production organization is affected by which form of agency the Managing Principal selects. Therefore, it is reasonable to assume that the structure of production organization is not arbitrary and is affected, at least partially, by the qualities of R&D agency. An examination of the three production examples given in the Introduction helps to clarify the foregoing.

Automobile vs. Jet Aircraft Engines

Automobile and Jet Aircraft engines require production techniques dissimilar to those of the final good, and are thus subject to innovations which may have no beneficial effect on production of the other subcomponents constituting the final good. Because the subcomponents are complex, the production organization of innovations should be strongly affected by agency concerns. As the source of motive force for both vehicles, innovations that decrease fuel costs or maintenance costs would have substantial worth to the Ultimate Principals in each case.

The Ultimate Principal for airliner production is an airline, an entity procuring numerous units and desiring utility for at least twenty years. When purchasing an airliner, an airline selects which of several engine manufacturers will supply engines. This is not surprising since airlines maintain the engines in their fleets and have substantial investments in engine tooling and training that is often specific to the engine manufacturer. Given the airline's investment in aircraft and engine maintenance, innovations in jet engines are often incorporated into an airline's existing fleet by swapping out innovated engines for old engines. Given the nature and needs of the airlines, the aircraft manufacturers make engine removal/replacement uncomplicated and design a new aircraft in conjunction with the various engine manufacturers so that common interfaces are employed.

The Ultimate Principal relative to automobile production is the car buyer, usually an entity procuring one unit of production and desiring non-commercial utility for five, or perhaps, ten years. The average car buyer will not be swapping out engines or even maintaining the engine in his car. The average car buyer will wish to be able to find service that is dependably expert in the technologies incorporated into his car engine; thus, there is reason for a car manufacturer to maintain substantial control over engine innovation and production. All the same, engine innovation is not completely internalized. Automobile manufacturers find value in sponsoring the auto racing industry, a specialized sliver of the automobile market populated by Managing Principals with an intense interest in innovation and substantial assets of funding and engine knowledge. These specialized Managing Principals can direct and assist the internal agents of the automobile manufactures who have been charged with engine innovation.

Suspension Design vs. Production

Unlike automobile engines, higher performance suspension system innovation may be contracted outside of the automobile manufacturer yet production retained. Automobile manufacturers that specialize in high performance vehicles (e.g., Porsche, Mercedes, Lotus) tend to internally innovate suspension system design. General use automobile manufactures that wish to compete in the high performance market may opt to externally contract suspension system innovation. With reference to the analysis of this thesis, the price of internal agency ($b-\lambda$) for the large general use manufacturer would seem to be higher than the external contracting costs of specialized suspension system innovation. This may be partially explained by the observation that Lotus is, in the language of this thesis, a performance seeking agent. For instance, as a manufacturer of vehicles at the 'high-end' of the performance market, Lotus may consider an R&D contract with an automobile company whose performance vehicles are at the 'low-end' of the market as providing a subsidy for its own R&D. Lotus may find this subsidy arrangement sufficiently appealing, and the 'low-end' competition sufficiently non-threatening, that a long-term interest in maintaining the subsidy results in an incentive compatible relationship.

Purchase of Subcomponent or Production Licenses

The fundamental innovations behind the artificial sweetener NutraSweet and the compact disc data storage system are protected by patents, yet in the former case the patent holder is a subcomponent supplier whereas in the latter case the patent holder has sold licenses allowing competitors to internally produce its innovation. As a complex chemical compound, NutraSweet production requires substantial, yet easily scalable, investments in plant and equipment. As an ingredient in food, substantial market entry restrictions from the Food and Drug Administration deter entry of 'copy-cat' products. Compact disc technology suffered from no similar governmental restrictions on market entry, yet as a data storage technique its market worth was only secure if it could become an industry standard (recall Sony's experience with the Beta video recording innovation). With reference to the analysis of this thesis, the price of internal agency ($b-\lambda$) for circumventing the NutraSweet patent is too high, whereas the effective cost of circumventing the compact disc patent was so low that the patent holders had the incentive to license the technology.

All of these examples are taken from the private production economy. The choice of production organization need not have been consciously made by the Managing Principals in each case -- market forces might just as well have lead production to such organizations. As a Managing Principal, IBM so dominated the supply of computing equipment to the purchasers of computing resources that the concentration of market power was akin to a monopoly. Over the last decade, innovations in hardware, software, and user awareness of the utility of computing have reshaped production organization, and market share structure, in the computer industry. With a radically shrunken market share and billions of dollars of operating losses, no one would accuse IBM of wielding monopolist power. At the same time, the production organizations that have proven to be more successful responses to (or stimulators of) innovation need not have been optimally divined by the Managing Principals that have outstripped 'Big Blue' (e.g., Apple and Compaq). Over time, market entry should accommodate optimal adaptation of production organization to subcomponent innovation.

The same may not hold for Public Sector production organization. The Mars Observer experience, utilized in this thesis to point out the pitfalls of disregarding agency concerns in R&D subcomponent production organization, is an example of a type of production that may be considered a Public Monopoly. The production of planetary science knowledge in the United States has always been the protected domain of the National Aeronautics and Space Administration under the authority of the U.S. government. Unlike the early days of manned exploration, government-to-government competition from the Soviet Union in planetary exploration was never strong or particularly credible. Where public procurement is desired and private provision is not tenable, the governmental Managing Principal must be aware of the agency implications of R&D subcomponent production organization if wasteful individual procurements and eventual bloated public institutions are to be avoided.

References

Alchain, Armen A. and Demsetz, Harold, "Production, Information Costs, and Economic Organization," *The American Economic Review*, vol. 62, no. 5, 1972.

Casani, John, Official JPL letter to Trainer, Dr. James H., November 17, 1989.

Coase, Ronald H., "The Nature of the Firm," *Economica*, New Series, vol. 4, 1937.

Evans, David, JPL Interoffice Memorandum to Kane Casani, March 20, 1990.

Evans, David and Casani, Kane, JPL Interoffice Memorandum to Casani, John, June 11, 1990.

Evans, David, Official JPL letter to Weintreb, Marius B., July 5, 1990.

Giberson, Walter (JPL ALD), Handwritten note on a copy of JPL Interoffice Memorandum of Purdy, William, March 9, 1984.

Guesnerie, Roger and Laffont, Jean-Jacques, "A Complete Solution to a Class of Principal-Agent Problems with an Application to the Control of a Self-Managed Firm," *Journal of Public Economics*, vol. 25, 1985.

Holmström, Bengt, "Moral Hazard and Observability," *The Bell Journal of Economics*, Spring 1979.

Klein, Benjamin, Crawford, Robert G., and Alchain, Armen A., "Vertical Integration, Appropriable Rents, and the Competitive Contracting Process," *The Journal of Law and Economics*, vol. 21, no. 2, 1978.

Laffont, Jean-Jacques and Tirole, Jean, "Using Cost Observation to Regulate Firms," Journal of Political Economy, vol. 94, no. 3, 1986.

Malin, Dr. Michael C., E-mail message to Thomas E. Thorpe, June 15, 1990.

Mars Observer Budget Status Report, presented to Dr. W. Huntress, March 6, 1991.

Mars Observer FY90 1st Quarterly Review, December 5, 1989.

Mars Observer FY91 3rd Quarterly Review, May 16, 1991.

Mars Observer Project Management Report, JPL D-1104, June 26, 1986.

Mars Observer Project Management Report, JPL D-1104, November 20, 1986.

Mars Observer Project Management Report, JPL D-1104, July 28, 1989.

Mars Observer Project Management Report, JPL D-1104, October 26, 1989.

Mars Observer Project Management Report, JPL D-1104, December 21, 1989.

Mars Observer Project Science Group Meeting Minutes, First Meeting, F. Palluconi, and Section L, April 23 and 25, 1986.

MGCO Project Management Report, JPL D-1104, March 23, 1984.

Myerson, Roger B., "Incentive Compatibility and the Bargaining Problem," *Econometrica*, vol. 47, no. 1, January 1979.

Myerson, Roger B. and Satterthwaite, Mark A., "Efficient Mechanisms for Bilateral Trading," *Journal of Economic Theory*, vol. 29, 1983.

Polk, Charles, *Mars Observer Project History*, JPL D-8095 (internal document), December 1990.

Polk, Charles, *Incentive Contracting for the MESUR Mission: Pathfinder and Network*, JPL Briefing to the MESUR Advisory Panel, April 4, 1992.

Ross, Stephen, "The Economic Theory of Agency: The Principal's Problem," *The American Economic Review*, vol. 63, 1973.

Tan, Guofu, "Incentive Procurement Contracts with Costly R&D," *Caltech Social Science Working Paper 702*, June 1989.

Tirole, Jean, "Procurement and Renegotiation," *Journal of Political Economy*, vol. 94, no. 2, 1986.

Williamson Oliver E., "Transaction-Cost Economics: The Governance of Contractual Relations," *The Journal of Law and Economics*, vol. 22, no. 2, 1979.