OBDURACY AND THE STEERING OF PRIVATE SPACEFLIGHT

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CONTENTS

LIST OF TABLES

LIST OF FIGURES

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ABSTRACT

This dissertation examines the ability to re-choose and reshape technological development through the case of the privatization of spaceflight in the United States. In general this dissertation asks: How can contemporary technological development be structured to leave future technological choices as open as possible to future consideration? And what are the barriers to reshaping technology? The set of barriers I am studying I refer to as "obduracy." Accumulation, lock-in, path dependence, and technological momentum jointly render technological systems difficult to modify, entrenching certain outcomes that are good for some groups at the expense of most others and broadly barring against improvements based on learning by doing. This situation exemplifies obduracy. In order to show how obduracy becomes a barrier to re-choosing I show how privatization was partially the result of an accumulation of decisions at NASA rather than a strategy arrived at through deliberation and analysis, how economistic values and private executives have become locked-in to decision-making, how the available potential choices for space development are curtailed by the influence of private executives, and how this influence is expanded through technical, organizational, infrastructural, expert, and legal momentum. The dissertation ends the analysis of each facet by proposing an "intelligent trial and error" approach to the structure of decision-making systems. As a result, this dissertation contributes to reconstructivist science and technology studies, making it a potentially useful tool for partisans wishing to make space development more responsive to a greater diversity of people.

1. Introduction

1.1 Justification

How will humanity expand outward into space? Once the first Mars colony emerges, or the first asteroid is mined, will we get another try? Painted in the broadest of strokes, there are only two ways in which a civilization might proceed with the development of outer space: blindly plunging forward or intelligently with an eye for learning. Blind plunging might be characterized by a lack of effective mechanisms allowing for targeted assessment and selection between different development pathways and by strong incentives for accelerating innovation but disincentives for easing its pace or stopping it. Proceeding more intelligently may be characterized by institutions designed to evaluate space development, identify and respond to unanticipated errors both technical and social, and mitigate the harms resulting from those errors (Weiss and Woodhouse 1992; Woodhouse and Collingridge 1993; Swearengen and Woodhouse 2001). Thus, it seems wise to ensure that as development proceeds alternative choices remain practicable and that once development is complete it remains as open as possible to future modification.

The harms of sociotechnical systems cannot be well predicted at the outset, when steering them would be easy, but by the time enough is known about their problems to act with confidence, change has become exceedingly costly and difficult (Collingridge 1980, 17–19). Even when harms are known, costly and difficult change can make it difficult to resolve the causes. The general purpose of this project is to examine strategies for overcoming barriers to the openness of future technological decision-making. How can prospects for re-choosing be feasibly maximized? To do so, I examine the case of the privatization of spaceflight in the United States. How has spaceflight been structured to remain open or to close down options?

What barriers have been erected against such openness? Can the case of private spaceflight reveal ways of reducing these barriers?

The commercial development of outer space is no longer limited to science fiction. Private space development companies have participated in a rapid pace of technological innovation, have a substantial capital value, support important sectors of the communication industry, and have developed a robust set of legal supports. In 2010 the National Aeronautics and Space Administration Authorization Act (Rockefeller 2010) targeted $12.5 billion for commercial crew, cargo, and launches (Rockefeller 2010; Hackler and Wright 2014; NASA n.d.). That number keeps going up and Congress recently created legal support for the exploitation of space resources, such as asteroid mining, and extended restrictions on federal regulations of private space development activities through the U.S. Commercial Launch Competitiveness Act (McCarthy 2015).

Despite what I expect would be a broad consensus in favor of more intelligent space development, most wealthy western nations proceed largely through blind plunging. Though one could likely recall some examples of development occurring intelligently, such examples tend to be the exception rather than the rule. It has become common for analysts and pundits within space policy to treat privatization of space development as an inevitability, or part of a "natural" evolution from public to private. In his congressional testimony Robert Walker, former chair of the House Science Committee and board member of Space Adventures and the Space Foundation, described the "inventiveness of the free market" as the way to fulfill "our destiny among the stars." Academic analyses also portray privatization as part of a natural trajectory of development. Collins and Autino (2010) argue, "the failure to develop passenger space travel has seriously distorted the path taken by humans' technological and economic development since

WW2, away from the path which would have been followed if capitalism and democracy operated as intended" (1561). Such simplistic, apolitical ideas of technological progress have been dismissed and universally rejected by STS scholars (Winner 1977; Noble 1979; Winner 1986; Bijker, Hughes, and Pinch 1987). What makes space development in particular seem like it proceeds autonomously, and why do some space policy analysts perceive privatization as the keystone to such development? What are the barriers to the various facets of more intelligent development of outer space? Who can overcome those barriers, and how?

1.2 Conceptual Approach

The goal of this dissertation is to maximize the capacity within spaceflight for re-choosing and reconstructing. It may be that spaceflight and space development must undergo some sort of political, economic, technological, or social reshaping in order to help more people more of the time. The greatest barrier to reconstruction for a private approach to spaceflight is the same as for a U.S. governmental, internationally cooperative, or any other approach to moving outwards from Earth: obduracy that reduces the prospects for future modifications based on learning by doing. Thus, an analysis based on obduracy is widely applicable. Analysts might find obduracy in public or private projects, cooperative or isolated ones as well. Each would present particular challenges to re-choosing. However, I happen to be writing at a point in history when the space program begins to move in the direction of privatization.

Privatization has the potential to bring about particular sorts of obduracy to varying degrees because corporate executives sometimes intentionally seeks to freeze out competitors, protect against public "interference," and lock-in technological and other advantages (Lindblom 1982, 2001). More substantively, the so-called private sector tends to be less fussy than contemporary democratic governments regarding labor abuses, environmental considerations, and appropriation of resources from have-nots in order to meet the wants and needs of haves. Obduracy would thus be important to consider no matter who was making the decisions, and no matter how space vehicles, cargo contracts, asteroid minerals, and other property rights were allocated. But with the primacy of a privatized approach to contemporary spaceflight, it seems pertinent to ask: are there particular mechanisms inherent to this mode of governance that may increase obduracy?

But what do these commercial or private activities entail? Even within the industry it is unclear what counts as private, commercial, NewSpace, or something else. The Commercial Space Launch Act of 1984 provides a broad and somewhat self-referential definitions of commercial spaceflight as a “private application of space technology” which has “achieved a significant level of commercial and economic activity” (Akaka 1984). The Center of Excellence for Commercial Space Transportation, established by the Federal Aviation Administration (FAA), references “partnership between academia, industry, and government” (Price 2010). Scott Pace, the Executive Secretary of the National Space Council, argues that private spaceflight simply refers to spaceflight activities conducted by private companies, whereas commercial refers to fully marketized spaceflight activities: “private operators, private capital at risk, private demand” (Pace 2016). It is unclear whether definitions should focus on the sources of funding, the ownership of technical artifacts, market competition, or some other criterion. Perhaps the most illuminating definition comes from the Space Frontier Foundation, which defines NewSpace as “People, businesses and organizations working to open the space frontier to human settlement through economic development” (“What Is NewSpace?” n.d.). Existing definitions are likely to implicitly support current ways of doing things, so I will use a broader definition, but opening up space through economic development speaks to a common thread.

This dissertation focuses on the increasing influence of market oriented ideologies in the governance of spaceflight and space development. I will refer to this, generally, as privatization; this term will stand in for the process through which agenda-setting and decision-making are increasingly conducted utilizing market values, market processes, and conducted by business interests.

Obduracy occurs through a process where technological decisions accumulate. Systems become larger, more complex, and more determinant of their environments, thus perpetuating their politics unless sufficiently resisted. As obduracy increases, it decreases the extent to which policies are made explicitly, decreases the number of partisan groups which have a say in agenda-setting and decision-making, decreases the diversity of pathways for development which seem feasible, and increases the complexity and size of technological systems. Some examples might help to explicate the concept of obduracy. Let us examine automobiles. There is little ambiguity over the negative effects of auto exhaust, and several studies indicating negative social effects, such as a decrease in communality (Dotson 2017). Yet replacing cars in America seems like an impossible task. To take another example, despite a growing response against suburban sprawl, the links between the suburbs, car culture, the built infrastructure of cities, the economics of development, and the American dream itself all make the prospect of eliminating suburbs seem insurmountable. Such situations exemplify obduracy, entrenching certain outcomes that are good for some groups rather than others, and broadly barring against improvements based on learning by doing.

In the same way, obduracy may make it more difficult to modify space development. It inhibits the identification of potential errors and harms, reduces the incentives to make alterations which reduce harms, incentivizes complacency with the status quo, and muddies the identification of the causes of errors. If space development is obdurate, modifications based on learning by doing will be very difficult. The concept of learning is complex and multifaceted, but at a minimum it might include identifying problems, understanding their causes, and finding solutions which reduce those problems. Obduracy inhibits this process and thus as obduracy increases, it erects more and greater barriers to learning by doing.

Obduracy may also hinder democratic governance. Has private spaceflight been subjected to conscious and collective deliberation? How many partisan groups have had a substantial say in selecting this direction? Analytic attention to the democratic principle of autonomy, that citizen should have a say in decisions that impact their lives, will enhance the analysis of obduracy. Beyond this, obduracy represents a gentle tyranny of the past over the future. If private spaceflight does, indeed, have some chance of increasing its obduracy, then it may be that a substantial and seemingly unalterable space-economy will be an inheritance of future generations without having had a choice. Some scholars have already expressed worry about democratic governance (Kay 1995; Billings 2006; Kaminski 2012), expansion of imperialist relationships between space-faring nations and the developing world (Redfield 2002; Basu and Kurlekar 2016), or labor or environmental abuses taking advantage of the unclear legal environment (Newman 2015; T. Brown 2012). These consequences are heavy burdens to place on future generations without making some effort to build in malleability which may enable the governance of spaceflight to be changed.

Additionally, one need not identify obduracy as a barrier to more democratic technological development to advocate that it should be reduced. Technology can come with tremendous benefits, but also extreme consequences. If humans set foot on and even develop other heavenly bodies in the near term future, the outcomes of spaceflight are likely to be very far-reaching. In addition, spaceflight is very complex, both the artifacts and the organizations require immense levels of coordination, and no single person completely understands how they work. Therefore, even though it may be possible to broadly understand the potential consequences, predictions are likely to be partial at best, and unlikely to accurately link consequences with their causal mechanisms. For example, the work schedule for astronauts is very challenging, so much so that the crew of Skylab 4 staged a one day strike to renegotiate their work schedules for the mission. SpaceX has already been the subject of multiple labor disputes, the most recent of which resulted in SpaceX agreeing to a settlement paying $4 million to 4,100 employees. One might reasonably prepare for such labor disputes to continue as private employees begin to work in space. But other questions soon arise. Will paying customers be expected to work? What are their labor rights? What rights should they have? What is the relationship between labor practices in space and those of related terrestrial industries? What is the relationship between current privatization practices and future labor practices? Predictability is limited by the scope of these questions and by the complexity of the endeavor. Even where prediction is possible, it is incomplete, and so errors must be corrected by some degree of trial and error.

1.3 Background

Scholars in STS as well as other fields have described similar phenomenon to obduracy. Some have used actor network theory (ANT) to address irreversibility and stabilization. Callon (1986) describes the process of translation, in which a single entity becomes the obligatory passage point, and thus the representative, for a particular network. As with the example of the scientists and the scallops, the actors in the network can rebel, and translation breaks down or an alternative translation develops. But what happens when it becomes unfeasibly difficult to go back to a situation in which multiple translations are competing, and the current translation determines subsequent ones? Callon (1990) calls this irreversibility. He argues that networks with numerous and heterogeneous relationships which have a greater degree of coordination are more likely to resist alternative translations and are thus more irreversible (Callon 1990). Akrich (1992) describes a similar phenomenon of network stabilization. Akrich's concept of stable networks builds on irreversibility. Once a network becomes irreversible, translation begins operating externally to the network. Rather than simply define the relationships between actors *within* a network, an irreversible translation becomes a stable basis for the creation of new networks (Akrich 1992).

Similarly, Hughes describes the phenomenon of technological momentum, which Hommels builds upon to introduce the concept of obduracy to STS from urban studies. Momentum shares many similarities with irreversibility, but Hughes takes a "large technological systems" (LTS) approach. Over time, technological systems grow in size, adding artifacts, people, and organization. The larger and faster the growth, the more that system influences its environment rather than the environment influencing the system (Hughes 1987a). For Hughes, the LTS of power generation consisted of the physical artifacts like generators, transformers, and transmission lines, but also organizations like manufacturing firms, utility companies, and investment banks. As they grow they incorporate more and more, such as regulations and laws, research programs and scientific books and articles, and natural resources like coal (Hughes 1987b, 1983). Similarly, when conceiving of spaceflight or space development as an LTS, I am referring to the launch vehicles and other technological artifacts, but also private companies, NASA, space laws, state investments, regulatory structures, funding models, and many other components. Each of these components has connections external to the system, for example the Department of Defense (DoD). The DoD, and other connections external to the system of space development, experience mutual shaping with space development, but are not necessarily part of the system under analysis.

Hommels builds on technological momentum and synthesizes it with other frameworks of analysis to show the ways in which urban technologies become obdurate. By obdurate, Hommels means that technologies can become difficult to change through constrained thinking about alternatives, embeddedness in networks, or being part of a persistent tradition, that is, a system with a great deal of momentum (Hommels 2005). Although obduracy implies more than just the fixity analyzed by Hommels, she shows the variety of mechanisms by which technologies can exert influence over their environment.

Such concerns, which seem particularly relevant to very large and complex technological systems like spaceflight, are often ignored in analyses of space policy. For example, Logsdon's (2011) analysis describes the policy confusion that occurred in the dramatic shift in governance towards privatization. With little coordination between congress and President Obama's administrative staff, Obama's proposed policy was a surprise, shifting dramatically from what congress expected or believed politically prudent. Though illuminating the process by which this shift took place, Logsdon offers a primarily descriptive analysis. The analysis is thereby limited to attend only to the two options under debate: state or market based spaceflight governance. More recently, Lambright (2015) analyzes the development of the COTS program as a policy innovation, but in doing so takes for granted that the alternative to a state run program is one driven by market mechanisms. He argues that the only barrier to private spaceflight was getting the idea on the agenda.

The analysis of this dissertation focuses less on how technological policies came to be and more on how they should proceed from here. Such descriptive projects, while necessary, do not address the problem that “means are not crafted and selected to meet carefully chosen ends” (Woodhouse and Patton 2004, 6). Most technological systems are not structured to meet social ends: they lack mechanisms for equitably distributing the costs and benefits of the technology, lack mechanisms for dealing with second and third order effects of innovation, and the market transactions that drive them incentivize actors to ignore third parties who would still be effected (Woodhouse and Patton 2004, 6). Winner (1977) refers to *technological somnambulism* to describe this problem in which the seeming autonomy of technological development leads people to ignore the ways in which technologies shape their everyday lives, as if they were “sleep-walking” and oblivious to their surroundings.

Given these barriers, Woodhouse and other reconstructivists have argued that “learning from experience is the main way that sociotechnical activities become successfully shaped” (Woodhouse 2013, 68; Woodhouse and Collingridge 1993; Lindblom and Woodhouse 1993). Some form of trial and error learning likely already occurs in all areas of technological policy making. Decisions are necessarily made with imperfect predictions and so policies are adjusted as decision makers grow to understand their outcomes. The main difficulty in effective implementation of trial and error learning is a misalignment between identifying errors, correcting for them, and their consequences. Catastrophic consequences may occur before errors are identified, catastrophic consequences may occur before errors can be corrected, and errors leading to catastrophic consequences may not be corrected at all (Joseph G. Morone and Woodhouse 1986; Woodhouse and Collingridge 1993; Woodhouse 2013). Because obduracy is a barrier to identifying errors, developing strategies against errors, and reduces incentives for error correction, reducing obduracy would help alleviate these problems.

Given that obduracy is a contributing factor to this problem of seemingly autonomous technological development, trial and error strategies are likely to increase the prospects for more active steering. In other words, improving trial and error may enable more people to create technologies which better serve their chosen social ends by reducing obduracy. By applying the existing STS analysis of large technological systems, my research offers a conduit for improving thinking about spaceflight and space development. Rather than being an inevitable next step in the evolution of spaceflight, governance through market mechanisms is the contingent product of technosocial politics. Private spaceflight is socially constructed, and not the result of an autonomous technological imperative, therefore spaceflight could also be otherwise. I explore how growing obduracy gives the impression that spaceflight technology develops autonomously along the trajectory of market governance. Woodhouse (2005) suggests that counterfactual historical research is a particularly promising new path for researchers "interested in developing usable knowledge" (201). Usable research focuses "on barriers and prospects for designing, constructing, and diffusing technologies differently" (Woodhouse 2005, 201). Woodhouse and Breyman (2005) focus on barriers to show how green chemists are structurally similar to social movements and the ways in which they reconstruct chemical technologies. More recently Galis and Hansson (2012) utilize a counterfactual method to show how the interests of powerful fossil fuel actors become barriers to mitigating climate change. Similarly, I address how overcoming obduracy is a step to a more pluralistic vision of spaceflight.

But how can obduracy be overcome or reduced? As part of the reconstructive body of STS research, this dissertation will propose improvements as well as identify problems. I have utilized the framework of Intelligent Trial and Error (ITE) to guide my thinking towards this goal. The framework of ITE, developed by political analysts of technological change (Joseph G.

Morone and Woodhouse 1986; Wildavsky 1988; Woodhouse and Collingridge 1993; Woodhouse 2013), focuses on strategies for contending with unanticipated and unintended consequences of technological development and innovation. Their research focuses on risky technologies and organizational mistakes, advancing political concepts of deliberation and fairness. Broadly speaking, the idea is that appropriate implementation of democratic processes in conjunction with praparation for learning will improve technological innovation. While I do not directly apply this framework to the problems I identify in various case studies, I take this framework as a starting point for developing strategies to improve the implementation and development of technologies for space development.

1.4 Contribution

In my investigation of private spaceflight, I have found that space policy and space development are not often deliberative. Often, even insiders do not often shape space policy with thoughtful intent. Instead, many policy decisions are the result of the accumulation of events, decisions, and other factors. This has led to an increasing and problematic obduracy. Market values have been increasingly incorporated into spaceflight governance and its associated technological development. Thus such values have become routinized and industry interests have become locked in to agenda-setting and decision-making. One result of this process is that potential alternatives for moving outward from Earth have been excluded without comparable consideration. Another result is that private interests become increasingly influential. Private industry interests and values wind up directing technical, organizational, legal, and human components with increasing influence. The net result is a space policy in which it is very difficult and costly to make alterations in general.

Such difficulties in sociotechnical steering are underemphasized in STS and policy-making. For instance, when Godin (2006) examines the construction of the linear model of innovation he unsurprisingly finds that this model was socially constructed by a group of industrialists and other interested actors who proceeded to incorporate it into metrics for measuring productivity and allocating resources. But like many other studies in STS, Godin focuses on the academic contribution of the work, leaving the implications for improvement for other scholars. What have the impacts of the linear model of innovation been? And for whom? Moreover what are the barriers to replacing it? What alternatives might be better, and for whom? Similarly, Gieryn (2006) examines how analysts at the Chicago School of Urban Studies situated Chicago as the appropriate *place* to study urban design. By simultaneously situating Chicago as a field-site where the analyst could get up-close and personal with their subjects, but also as a laboratory where the analyst makes controlled observations which are true anywhere, Chicago became representative of cities in general. Gieryn too does not go so far as to explain the social significance of his findings (Henke and Gieryn 2008). If the importance of place is constructed, then how should it be reconstructed? Which places *should* be granted importance? Both works represent a fairly standard form of study and analysis in STS, they establish a foundation in which technological development could have been otherwise, and leave an obvious next step for a partisan vision or idea for what could be done better.

Academics within STS are still in the early stages of taking that next step, and much important work remains. For instance, even those few scholars who elucidate possible reconstructions often do not provide any tools for how that reconstruction might be achieved and by who. For example, Stirling (2008) shows how interpretive flexibility is limited from the very beginning of the innovation process by preexisting dynamics of power and interest. Stirling thus identifies barriers, but not strategies for overcoming them. One reason may be that he does not frame power and interests as barriers. Doing so would make it easier to then analyze how to overcome them. What are the barriers to maximizing interpretive flexibility at the outset of a new technology? What processes contribute to these barriers? How might such barriers be minimized?

Had these scholars asked and answered questions similar to those I pose regarding spaceflight in section six of this chapter, it would not have reduced the usefulness to academics they already exhibit. Doing so would, however, make such scholarship more useful to interested partisans. For example, I ask how the ability to reconsider spaceflight development might be maximized. Had Godin asked a similar question, wondered how the influence of the linear model of innovation might be reduced, his analysis would not just have uncovered how that model was socially constructed, but also what barriers its construction erected to the application of alternative understandings of how innovation unfolds. I further ask in this dissertation how can the barrier of obduracy be minimized? In turn, had Godin identified groups of industrialists and other insiders as also erecting barriers to alternatives to the linear models, he might also have wondered how the influence of such interested actors may be reduced. He may have come to the conclusion that involving a more diverse set of interests into the innovation process, perhaps by selecting which problems innovators seek to solve. In short, asking the sorts of questions which I pose in this dissertation would have enabled Godin's scholarship to be of more use to partisans seeking to contest the linear model of innovation. Too often, such reconstructive and practically useful, partisan scholarship is absent in STS scholarship. Thus this dissertation contributes to similar lines of reconstructive scholarship.

1.5 Objectives

This project provides a partisan sociotechnical analysis for those that desire a more careful approach to moving outward from Earth. It takes the explicit position that even as technological developments begin closure, opportunities for reopening development pathways to reconsideration should be maintained. As such, my goal is not to dissuade those in favor of increased commercialization from this pathway, although the analysis in this dissertation may help some of them recognize the need to temper their support with an eye for reducing obduracy. Instead, the purpose of this dissertation is to help those who are dissatisfied with the options on a single spectrum from government to private spaceflight better understand the barriers erected to potential alternatives, as well as how they might begin to devise strategies for overcoming those barriers to reconstruct spaceflight and space development for the future.

Although some social scientists are cautious about explicitly normative scholarship, to an extent partisanship in scholarship is unavoidable. Rather than attempt to back away from normative positions that might enhance the social relevance of this project, I instead focus on reflexive acknowledgement of the partisanship of my normative claims. This project is informed by “thoughtful partisanship” as described by Lindblom (1986). Thoughtful partisanship does not reflect a lack of rigor, unfair, or dishonest use of evidence. Instead it is an acknowledgement that some values are inevitably reflected in all scholarship. The alternative can often be thoughtless partisanship. For example, in the debate over the safety of commercial spaceflight, actors hid their preferences for or against commercial spaceflight options behind technical definitions of safety, undermining a clear goal for safety (Bouchey and Delborne 2014). I present an alternative to such a dichotomous debate by suggesting that malleability is valuable and providing an analysis identifying barriers to such openness and suggesting possibilities for doing better. In this regard, I do not attempt to treat private and public spaceflight options in a neutral or objective manner. The suggestions I will pose as throughout my analysis would, were they implemented, be injurious to some even while beneficial to others. In as far as the goal of this dissertation is to maximize openness to future modification, I am willing to damage contemporary space businesses in order to ensure a greater benefit to larger portion of those future generations who have yet to have their say. Thoughtlessly partisan research would hinder rather than improve the development of structures to deal with obduracy of technological systems. The goal of this project is not to convince private spaceflight advocates to change their minds. Nor is the goal of this dissertation to demonstrate superiority of any one option for spaceflight over another; it does not seek merely to argue against private spaceflight or replace it with some other option which might still become obdurate. After all, spaceflight is bound to be replete with shortcomings for some partisans however it is conducted. Instead, this analysis advocates for a greater capacity for reconstruction and shows some specific areas in which the various factors of obduracy make reconstruction difficult in order to suggest how each factor might be minimized.

The broadest goal of this research project is to develop an analysis useful in structuring technosocial action now to preserve the openness of future choices. Is obduracy for spaceflight the same as obduracy for other sorts of policies? The more obdurate technological systems become the fewer alternatives there seem to be for decision makers to choose from. Such systems are difficult to steer and thus it is difficult to avoid unintended consequences. Although the focus of this dissertation is on the privatization of spaceflight, obduracy has a broad relevance. Other forms of development may also show varying degrees of obduracy. Are there substantial differences between the obduracy of the extractive industries on Earth and those proposed for outer space? If not, analysts may find that many of the consequences of mining, quarrying, and oil and gas extraction that many people have simply accepted as the cost of progress are not, in fact, as inescapable as they may seem. The examination of emerging transportation technologies like self-driving cars may also benefit from the use of obduracy. What transportation problems are solved by making cars self driving? What other conceptions of those problems could have led to different technological (or social) solutions? Are there alternatives to self-driving cars that have already been excluded without consideration? Examining such cases using the concept of obduracy can elucidate potential alternatives worth pursuing, and may raise questions about the perceived inevitability of tradeoffs from legacy technologies which have simply been accepted.

The relevance of obduracy stems from moving beyond description. Obduracy is not merely a property of technological systems; it is a barrier to be minimized. While STS tends to focus on description and diagnosis of problems, this project uses obduracy as a tool for analyzing alternative governance structures and policy frameworks for spaceflight and space development. The movement from examining the obduracy of spaceflight to identifying and counteracting barriers it erects refocuses the project towards future decision-making. Rather than treating obduracy as an unavoidable property of technological systems, I understand obduracy as something that can be opened to a repertoire of actions undertaken with the goal of achieving better steering and better governance. By the end of this project, I will have established a thorough understanding of obduracy, how it forms, and how it may be mitigated. My goal is for readers to come away with a foundation for better, more intelligent spaceflight policies, as well as an analytical tool to apply for realizing more malleable, more democratic technological systems.

1.6 Research Questions

This dissertation builds on STS analyses to understand how obduracy relates to the privatization of spaceflight. It asks, broadly, how can contemporary technological development be structured to leave future technological choices as open as possible to reconsideration? In the language developed in this dissertation, how can technological development be structured so as to minimize or reduce obduracy? To do this, my analysis begins with a concern for how space development could proceed differently, rather than only either celebrating or lamenting the direction in which it seems to be developing. Even political resistance to private spaceflight all too often takes the form of claiming it is too soon for private spaceflight to succeed. Thus the implicit assumption shared by both "sides" is that markets take over what has been pioneered by the state (Gerstenmaier 2012a; Pulham 2013). Rather than take a similar approach, this dissertation examines the extent to which private spaceflight has been historically structured to reduce or enable obduracy.

As such, I explore obduracy as a barrier to the ability to adjust technological systems in response to learning about the harms they inflect. How can decision makers minimize barriers to selecting alternatives? What are the characteristics of obduracy? How do these characteristics manifest to construct barriers to leaving spaceflight open to alternatives? I utilize several inquiries related to each facet of obduracy in order to answer these main questions: What shifts in values for the space program have accumulated over its history? How exactly has the political arrangement of privatization been locked in vis-à-vis the sociotechnical system of space development? To what extent, and which, alternative pathways for space development are being excluded? In what ways have the responses to longstanding design and organizational problems by private spaceflight executives and their employees acted as potential catalysts or causes of increasing technological momentum of private spaceflight? Framed within these queries are the questions: who wins and who loses? And how can obduracy be reduced? Many past failures in spaceflight can be traced to some sort of inflexibility. For example, many of the political, financial, and safety issues NASA had with the space shuttle could have been avoided with a more flexible design (Collingridge 1990). Some policy makers hope that allowing market mechanisms to take over much of the task of governing spaceflight will alleviate some of the barriers to space development. But little attention has been given to thinking about what else may have been done. How much decision making can be attributed to active steering towards some spaceflight goal rather than slow and inattentive accumulation? To what extent have varying publics been included in agenda setting and decision-making processes? Rarely has the question been asked, "could space development be changed in response to new needs or unintended consequences?" Could spaceflight be locking in to current trajectories because of this failure to govern spaceflight malleably?

1.7 Chapter Outline

In chapter two, I focus on fleshing out the concept of obduracy. In common lexicon, obdurate is an adjective referring to someone who refuses to alter their opinion or course of action, specifically in response to attempts to change those actions or opinions. The usage here simply applies this idea to technological institutions/systems. Technological systems become obdurate as decisions accumulate and gather momentum, locking in pathways for future technological development and limiting potential alternatives. As a result, obdurate technologies resist and seem to resist attempts to direct and steer them, at least by most interested actors. Thus, obduracy reduces the prospects for future modification of technological systems based on learning by doing and acts as a barrier both to reducing the potential harms of technological systems and to maximizing the breadth of their potential benefits. However, obdurate technical systems are not unalterable. I have identified four facets of obduracy: accumulation, lock-in, path dependence, and momentum. Because obduracy does not have its roots in any one policy position or inflexible technical artifact, it requires reconstitution through constant maintenance. If business as usual changes, then seemingly unalterable obduracy may dissipate on its own, as it ceases to grow from continual accumulation. This project suggests how to reduce future obduracy in emerging sociotechnical systems and how currently obdurate systems might be made more malleable. The remaining chapters each focus on one of the components of obduracy: accumulation, lock-in, path dependency, and momentum. The chapters examine each component through carefully constructed histories, some contemporary, of spaceflight and space development, simultaneously developing the components of obduracy and applying them in an analysis of spaceflight.

Chapter three examines how accumulation contributes to obduracy through a historical analysis of who staked out the policy position of privatization and how. The accumulation of decisions, events, and factors is a necessary component of obdurate sociotechnical systems. At the macro level, the accumulation of decisions, events, and factors look no different than an explicitly staked out policy position. But no actor or group of actors ever articulated such a position. In certain domains, certain policy decisions are structured to be made by practice rather than by deliberation. Accumulation, thus, draws attention to the major policy positions that get staked out inadvertently. Although these policy positions are made inadvertently, they are not unintentional, in so far as some interests are structurally over represented and proximate decision makers push policies towards those positions rather than others. Accumulation points to how such processes do not necessarily happen overtly, relying on the every-day practices and routines which seem relatively innocuous to settle policy positions with uneven benefits. What causes accumulation? How has it contributed to contemporary private spaceflight? This chapter presents several historical vignettes which show how the contemporary policy position of governance via market mechanisms is the result of accumulation.

Chapter four demonstrates how lock-in contributes to obduracy. Examples demonstrate the extent to which private interests shape the goals and values of space development. Lock-in means simply that once a technological trajectory has become locked in, it is very difficult to select an alternative regardless of the potential benefits. Lock-in occurs when accumulation in favor of one particular systemic configuration over others leads to a runaway effect (Arthur 1989, 1994b). More than technology can become locked in, social groups, partisan actors, values, and interests can become locked in to decision-making and agenda-setting positions as well. The lock-in of technologies and partisans therefore locks in political winners and losers as well. It is implied, whenever a technology or partisan group gets locked in that some competing technology or partisan groups get locked out. For example, because valuable asteroids are usually not the same as asteroids that pose the greatest risk to the Earth, an asteroid survey in which the interests of asteroid mining companies are locked in will lock-out the public interest of planetary protection. Attention to both lock-in and lock-out emphasizes the importance of alternatives. Early superiority of one option may lead to lock-in but is no guarantee of long term advantages, and thus it may be that those alternatives which become locked out are superior in the long run (Arthur 1989, 1994b). This chapter examines the connection between market governance in spaceflight and the potential for lock-in.

Chapter five shows how obduracy leads to path dependency by comparing established pathways for development to those alternatives which have not been seriously considered. Path dependence results when accumulation limits the available potential technological trajectories for the future. Path dependence has often been described as "history matters," meaning that historical choices influence present and future potentials. Thus the same applies to choices made in the present day. "The development of new technology thus depends on characteristics of the existing technological regimes and the overall sociotechnical landscape" (Kemp, Rip, and Schot 2001, 276). But all human society is historically dependent. What makes path dependence important is that it is a kind of irreversibility in which technological change is influenced by its antecedents. Kranakis (1988; 1989; 1997) describes how immediate institutional structures, such as patent systems and community structures, circumscribe themselves into the pathway of technological development at the very level of design. The pathways which are selected through this process are always social and political. Often some interests may participate in the selection of pathways while others cannot. Path dependency presents itself as a gentle tyranny over the future by the past and over most interested parties by some small elite group, thus preventing adjustment in response to any unintended consequences that may arise. Mars has become the predominant destination for human exploration. As long as this is the case, even private companies such as Planetary Resources which are oriented towards human spaceflight infrastructure still provide support for Martian exploration without having to explicitly endorse it. Are other options for destinations feasible? If so, what factors have led to the limitation of potential destinations? Which social and political pathways correspond to which development pathways? Other destinations might have alternative foundations which are worth consideration.

The sixth and final substantive chapter utilizes the theory of technological momentum. It examines whether contemporary market oriented spaceflight exhibits signs of building momentum. Technological momentum as developed by Hughes (1969; 1987; 1994; 2000) plays a key role in the development of obduracy. Hughes takes the concept of momentum from physics as a metaphor for large technological systems. A system with large momentum is more difficult to turn from its development path. The more technical, organizational, infrastructural, expert, and legal components contained within a system the greater its mass. The faster a system grows, the greater its velocity. Technological systems gain momentum as new innovations in each of the above categories add to the components contained with that system. While some innovations are revolutionary, giving rise to alternative systems, innovations that contribute to momentum instead solve well known problems, thereby entrenching existing interests. These problems, called reverse salients, often come in the form of sub-optimal systemic efficiency. So as actors innovate to solve the reverse salients within a system, they contribute to the increasing momentum of that system and those that benefit from it. Contemporary private spaceflight companies are innovating at a rapid pace, solving a myriad of what spaceflight executives consider important problems. Have these problems been well established in the field of spaceflight? Do these recent innovations increase efficiency or offer alternative approaches? No matter the answers to these questions, spaceflight is growing at a rapid pace. The scope of the influence of the technological system of spaceflight and space development has also increased. Thus, if these innovations are, in Hughes's terms, conservative, then the momentum of private spaceflight is likely to be increasing. Momentum is a clear barrier to more intelligent steering of spaceflight by trial and error and thus makes it more difficult for policy makers to respond to any harmful consequences which may occur.

2. Dimensions of Obduracy

2.1 Introduction

Consequences are too rarely emphasized in thinking about technological development. Outside of academia, technology is still largely viewed as a neutral tool or synonymous with progress (Marx 1987; Herkert and Banks 2012; Dotson 2015b). Even within STS, the focus of most social constructivist literature is on the origins of the technologies and their interpretive flexibility rather than the effects of technologies and their roles in shaping people's lives (Winner 1993; Brucato and Gano 2014). Obduracy provides a framework through which this dissertation seeks to understand the consequences of private space development for the ability to re-choose technological pathways. Privatization is only one possible way of moving outward from Earth. Without being able to predict the consequences of this choice, how can decision makers minimize the barriers to selecting an alternative should those consequences prove unbearable? This chapter develops obduracy as a theoretical framework to better understand what barriers exist to re-choosing the pathway of development for spaceflight and how to minimize them.

The purpose of this dissertation is to examine what governance structures might reduce barriers from each facet of obduracy to the ability to re-choose regarding private spaceflight and space development. But what is obduracy? What are the characteristics of an obdurate technosocial system? How do these characteristics manifest to construct barriers to leaving technological decisions open to future modification? What lessons about obduracy does the case of contemporary private spaceflight teach?

The remainder of this chapter will give a further detailed explanation of obduracy. This chapter constructs the concept of obduracy by first examining two related concepts, and building off of them. By introducing the concept of obduracy, I hope to use it to analyze the potential barriers to reconstruction that may already exist in private spaceflight and what interventions might reduce obduracy and maximize the capacity for making alternative choices in the future.

2.2 Definition of Obduracy

Obduracy is not an entirely new concept, and many other concepts share similar meanings and usages. Hommels (2005) provides three sources of obduracy: dominant frames, embeddedness, and persistent traditions. Collingridge (1992) provides the concept of inflexibility which describes how it comes to be that poor technological decision making can seem so beyond control. In this research, the concept of obduracy builds on these previous concepts. The concept of obduracy is designed to enable different groups of people to engage in different courses of action and decision making than either Hommels's conception of obduracy or Collingridge's conception of inflexibility.

For this project, obduracy is a process in which technological decisions accumulate. Systems thus become larger and more determinant of their environment. As their determinism increases, they perpetuate their politics and bar learning about alternatives unless sufficiently resisted. This resistance is extremely difficult, as obdurate systems perpetuate via business as usual, in other words, by the everyday decisions that often seem so mundane and inconsequential, made without a second thought. Like the sorcerer's apprentice, obdurate technologies are those over which we seem to have lost control. There is little ambiguity over the negative effects of vehicle exhaust, and yet replacing cars in America seems to be an impossible task. Despite an ever growing response against suburbia, its inextricable link to the American dream, car culture, the built infrastructure of roadways, and the economics of development seem insurmountable. Such situations exemplify obduracy, entrenching certain outcomes that are good for some groups rather than others and broadly barring against improvements based on learning by doing.

Does private spaceflight potentially exhibit similar obduracy? Answering this question first requires a more detailed understanding of obduracy's causes and consequences. The concept of obduracy I use in this research builds on and adds to concepts like Hommels's obduracy and Collingridge's inflexibility. While Hommels (2005) explicates several sources of obduracy, what to do about obduracy or its effects on human decision making are unclear. Collingridge (1992), on the other hand, is quite clear that inflexibility should be avoided and also about how to avoid it. This still leaves the question of how to deal with currently inflexible systems unanswered.

2.3 Building on Inflexibility and Obduracy

Often times, technological systems can seem to be autonomous, in that their direction does not seem to be influenced by human control. This can often come in the form of inflexibility (Collingridge 1992) or an unchanging technology (Hommels 2005), but it need not. It may more often be the case that people feel a loss of control precisely because technological change occurs at too fast a pace to keep up with. Such technologies are not actually autonomous. STS has convincingly critiqued the notion that autonomous technologies determine social life (Winner 1977; Bijker, Hughes, and Pinch 1987). Instead, I characterize such technological systems as obdurate. Obduracy, here, means much the same thing as the colloquial usage: a stubborn refusal to alter ideas or behavior even in the face of resistance. As such, technological obduracy refers to technical assemblages of people, artifacts, and organizations that are very difficult to steer in response to a desire or need for alteration.

Hommels (2005) uses the term “obduracy” to talk about urban design. Collingridge (1992) too developed the concept of inflexibility to address the problem of maintaining the flexibility of decision-making. What insights do these concepts give to examining prospects for re-choosing technological development pathways? How can thinkers interested in maximizing the potential for reconstruction gain from putting these concepts into conversation? How does the concept of obduracy which this dissertation introduces contribute to the analyses of Collingridge and Hommels?

2.3.1 Previous Concept of Obduracy

When Hommels defines obduracy, what problems does she envision obduracy addressing? How does her definition address those problems? Hommels uses obduracy as a way of understanding a contradiction between urban design and scholarship within STS. Urban spaces, to Hommels, exhibited a tremendous amount of fixity and seem to resist reinterpretation. Through this tension, Hommels defines obduracy as a sort of force that resists change through a variety of mechanisms.

The first way in which obdurate technologies resist change is through dominant frames. Frames are the “roles and strategies of actors” in technological decision making (Hommels 2005, 330). Dominant frames are “fixed ways of thinking and interacting” with technology (Hommels 2005, 331). An important part of their dominance, is that social groups that share those frame are “closed-in” to making decisions using it, while those that operate in competing frames are “closed-out” of technological decision making altogether. In this way, obduracy is not just the result of the technical properties of artifacts, but also of the interactions between social groups which are constrained by fixed ways of thinking (Hommels 2005, 334).

The second way that technologies can be obdurate is through embeddedness. Embedded sociotechnical systems are closely intertwined. Making changes to one requires making changes to at least one other, which presents a substantial barrier to such change (Hommels 2005, 337). Such embeddedness can cause crises as old technological systems once used for capital accumulation now become barriers to the development of new systems which are required for the generation and accumulation of new capital (Graham and Marvin 2001, 193–94; Hommels 2005, 336). For example, new urban development oriented towards international investment (such as high-rises, or other high-value rental properties) can inflate property values, driving up costs for existing local businesses and home-owners, driving them out of business or away from the area, resulting in a loss of local capital. The reduced income for the city compounded with the sunk investment in the new development make it even more difficult to undo the damage and proceed in a different developmental direction (Imrie, Thomas, and Marshall 1995). Again, Hommels emphasizes that obduracy here is not an "intrinsic property of technologies but can only be understood in the context of its ties to other elements within a network" (Hommels 2005, 337).

Finally, obduracy can result from persistent traditions. In this case, obduracy results not from the sociotechnical system itself, but from its *long term cultural context* (Hommels 2005, 338–39). Persistent traditions stress the roles of cultural norms which extend beyond the immediate time and local context of an obdurate technical system. Rules and norms of behavior create shared cultural visions of what a technology is supposed to be. These archetypical visions shape the design and organization of technological systems within a given culture. The cultural context of technological systems supports their momentum. At the beginning stages of a particular innovation, it is open and has interpretive flexibility, but then it begins to build momentum. As it does so, the design goes from being novel to being standard, and engineers and operators are trained in its use. When it becomes completely established, it can become foundational for new research. The education and research into the design formalize it within the relevant disciplinary culture, which contributes to its momentum. But, since persistent traditions are not context dependent, they can operate in broader or narrower cultural contexts than disciplinary culture.

2.3.2 Inflexibility

What problems does inflexibility address? And how does Collingridge envision the concept of inflexibility addressing those problems? Collingridge describes inflexibility as the most important "horn" of the dilemma of control: that the negative effects of a technology are difficult to predict and do not reveal themselves until the technology has become too inflexible to change in response. He argues that better prediction is not a viable option, so the best strategy is to focus on reducing inflexibility so that harms of negative technological outcomes can be reduced and the problems fixed more quickly through learning by doing (Collingridge 1980). Inflexibility has four properties (1) Long lead times, (2) large unit size, (3) high capital intensity, (4) high infrastructure dependence (Collingridge 1992). Because technologies with these properties are difficult to learn about and to change in response to the harms they cause, they are therefore more likely to be harmful. However, he also argues that inflexibility itself can be predicted and that if a technology is inflexible, then a more flexible option exists. Thus it is possible to identify the potential for inflexibility based on its four properties and to devise or discover a more flexible option. These properties of inflexibility create certain characteristics that are useful for analyzing inflexible technologies.

Inflexible technologies often benefit large business organizations while the risks are distributed to the public. This typically results from high capital intensity. Only the largest business enterprises can afford capital intensive projects, but such projects entail such a high risk that they would never get off the ground if those risks could not be widely distributed (Collingridge 1992, 15). Such a task is usually politically viable because the company has a high level of interest in convincing political decision makers to take on the risks, but since the risks are dispersed throughout the public, interest is often too low to build a powerful oppositional coalition (Stone 1997) or those social groups which are too disenfranchised to resist are given most of the risk.

Failures are likely to be very expensive. This holds true monetarily, but also technically, socially, and environmentally (Collingridge 1992). By investing such a large amount in the development of an inflexible technology, making changes in response to failures means high levels of sunk costs. The same can be said of large unit sizes, since each unit represents a larger percentage of the total investment. Because learning is slower, the harms of such failures are often left unknown and unmitigated for some time. As such, when inflexible technologies fail, it is hard to learn enough about the failure quickly enough to reduce harms.

Decision-making about inflexible technologies is often highly centralized with little debate. Centralization excludes most legitimate stakeholders, allowing those few remaining dominant organizations to shifts costs and negative repercussions to the public domain (Genus 2000, 26). Those groups who would be negatively affected by the inflexible technology are denied a voice in the decision. Despite barriers to opponents, the potential for opposition is high, as may be expected for technological projects with elite benefits and public risk. To avoid this, opposition groups, who would be exposed to the risks of the technology without many of the benefits, are strategically excluded from deliberation if such deliberation even occurs. Thus political groups that have legitimate interests are marginalized by inflexible technologies (Collingridge 1992, 15–16).

It is usually possible to develop more flexible alternatives instead, and do so with organizations which are less centralized. Because the inflexible option is often defended as the only viable one, it is important to remember that this is rarely true, and often merely serves to defend the interests of those centralized organizations and their small sets of decision makers who would benefit from the inflexible decision (Collingridge 1992, 16).

2.3.3 Synthesis of Obduracy and Inflexibility

Hommels's conception of obduracy and Collingridge's conception of inflexibility describe similar phenomenon but have divergent uses. Examining them in relation to one another can help to better understand how the version of obduracy presented in this research might be a useful tool for sociotechnical steering. What are the analytical differences between obduracy and inflexibility? In what ways might an analyst apply them concordantly?

One key difference between the two is the scale in which their concepts operate. Obduracy operates on a more general scale, while inflexibility is applicable on specific scales. Another way to present this difference, might be that obduracy is more theoretical and inflexibility is more applied. For example, Hommels uses obduracy to analyze urban design writ large, while Collingridge uses inflexibility to analyze technologies like the space shuttle and high rises. Thus inflexibility can add complexity to an analysis based on obduracy. Are there equivalent dimensions between obduracy and inflexibility? For example, does any dimension of inflexibility offer a micro-explanation of the embeddedness of political assumptions in a technological system?

Hommels focuses on sources of obduracy that are more sociopolitical than material. Design choices in cities are peripheral concerns in her analysis, social conceptions of the meaning of urbanity are more central. Collingridge is not focused exclusively on the material, but his attention leans in that direction, as might be expected, since inflexibility applies more to artifacts than systems.

One advantage of the concept of inflexibility is its applicability to particular technical systems or artifacts. Collingridge gives clear criteria for delineating the extent to which a technical activity is inflexible. Hommels's obduracy is analytically useful, but she does not make the same effort to deal with problems caused by obduracy. One can relatively easily apply Collingridge's analysis to any artifact and determine the degree to which it is inflexible. Hommels's obduracy, on the other hand, is useful for thinking through the ways in which technical landscapes do or do not change, but does not provide the tools to measure the extent of obduracy in a new case.

Knowing where the concepts diverge enables a more robust dialog between the two. Through socialization, many individuals hold frames that have come to be culturally dominant as a source of obduracy similar to the centralization of decision making that occurs with an inflexible technology, but on a broader scale. Dominant frames result in a closing-out of social groups that don't hold those frames (Hommels 2005, 331). In much the same way, inflexible technologies give an unfair advantage to the status quo in contests over their development and diffusion. Thus, when debate arises change is hotly resisted. As a result, problems with inflexible technologies often receiving Band-Aid fixes which only serve to settle the problem temporarily while also further entrenching the technology (Collingridge 1992). Thus centralizing decision making increases resistance to changing inflexible technologies, or as

Hommels might put it, dominant frames help produce obduracy, which she characterizes as a resistance to change.

Embeddedness is similar to what Collingridge describes as "entrenchment." Both refer to ways in which interconnectedness makes appropriate change more difficult. For Collingridge, entrenchment has a great deal to do with expense. He takes a more technical approach to his analysis in this way. Hommels, on the other hand, directly addresses sociopolitical opposition to change with embeddedness. Despite this general difference these concepts are not opposed, but rather two sides to same coin, explaining various ways in which connected networks of actors and technologies can lead to obduracy or inflexibility. Entrenchment is "the adjustment of other technologies to one which is developing, so that eventually control of the latter is only possible at the cost of re-adjusting the technologies which surround it (Collingridge 1980, 47). For example, the launch pads for the space shuttle are both enormously expensive to build and maintain, and are also built specifically to accommodate the space shuttle. Thus, when the space shuttle was grounded, there was not an alternative use for the launch pads. Additionally, when the space shuttle was canceled, future launch vehicle designs, including by commercial companies, attempted to accommodate use on the space shuttle launch pads (Collingridge 1990). Embeddedness might be described, then, as the inflexibility of a technology within a network. For example many urban technologies are embedded with foundations both literally rooted deep into the ground but also in financing and within the numerous interests that rely on their fixity (Hommels 2005, 336–37). Thus altering one urban technology entails several other alterations that will be resisted by those who stand to benefit from the status quo. The similarities between embeddedness and entrenchment show how using Hommels and Collingridge in concert can help analysts to move between technical and sociopolitical frameworks.

To account for long time scales, Hommels uses persistent traditions to show how culture can influence change in sociotechnical systems. While Collingridge does not explicitly engage in the ways in which long-term cultural traditions impact inflexibility, he does use other mechanisms to account for time. Inflexible systems usually get more difficult to fix over time. Users become more dependent on a technology the longer they use it, which presents a barrier to alternatives (Collingridge 1992). Avoiding inflexibility requires learning by doing. Learning takes time, and so to avoid inflexibility, technological designs must allow for time to learn from mistakes. This implies that technological development and diffusion must occur slowly enough that decision makers can learn from and react to problems and can weigh potential improvements (Collingridge 1980).

In conjunction, Hommels's theory of obduracy and Collingridge's theory of inflexibility provide a foundation for better understanding how to improve obdurate or inflexible technosocial systems. Hommels's version of obduracy is descriptive on a broad macro scale, but at the sacrifice of concrete recommendations for the abatement of obduracy where it is a barrier to better steering of technosocial systems. Collingridge, on the other hand, focuses on avoiding inflexibility, but has little to say about what to do with currently inflexible technologies. In contrast, my research explains how to reopen decision making in systems that are already obdurate or well on their way to it.

2.4 The Facets of Obduracy

Obduracy is best understood as consisting of several facets. Obduracy is not black and white, where a technical system either is or isn't obdurate. There are degrees of obduracy and different kinds. One system might suffer from one facet while a different system suffers from another facet. Thus obduracy is not one phenomenon that either does or does not describe a system.

What are the different facets from which obduracy can be comprised? How do these facets contribute to the increase or decrease of obduracy?

First, obduracy is the result of accumulation. Small seemingly insignificant decisions may accumulate and amount to a much more substantial result. Accumulation means that decision making, events, or other factors can have a compounding effect. One decision seemingly determines the next. One factor seems to determine another. Such a process may continue until the structure built up from numerous compounding decisions seems to be inevitable and difficult to alter. There is no one thing that pushes an obdurate system over the edge. Without an obvious causal mechanism, it is easy to naturalize obdurate technological systems.

The preeminent example of such a process is the adoption of technology in a situation of increasing returns (Arthur 1989). When the benefits to any given adopter are greater the more total adopters there are, any factors that give a sufficient boost in adoption will result in that technology totally dominating the market. For example, as more people chose to adopt VHS format over Beta in the competition over the VCR market, the more likely it became for future consumers to also adopt VHS (Arthur 1994a).

The important aspect of this example is that it does not in any way *require* actors to actively cultivate favorable conditions. Adopters may make their selection because more retailers carry the technology, because they already understand how to use the technology, because communities of support exist if they have problems, because they have seen it more, or for many other reasons (Arthur 2009). More generally, policy positions regarding the development of technological systems do not require explicit advocates for them to accumulate. Even though accumulation looks like an explicitly staked out policy position, accumulation is the result of decision-making by practice rather than deliberation. Engineers can simply solve problems, as they are trained to do (Riley 2008). Business leaders can merely maximize profits, as they are incentivized to do (Lindblom 1982). Accumulation is thus very powerful because it draws attention to how non-decisions and routine can be driving forces.

For example, the origins of nuclear power research largely neglected safety because taking advantage of seemingly low uranium supplies took priority for developers. Compounded onto this, initial development was influenced by the goal of using reactors in submarines and other naval vessels. Reactors for such purposes had to be compact, and needed to be developed quickly. When development for civilian reactors ramped up, the most work had been done on the navy’s submarine and carrier reactor program, so these developments were adopted for the civilian program (Joseph G. Morone and Woodhouse 1989). This accumulation of decisions and events leads to the use of large scale light-water civilian nuclear reactors, despite its unpopularity, inherent safety risks, and costliness. Is private spaceflight in a similar situation? If market governance in spaceflight is the result of accumulation similar to the way that nuclear reactors are, that may indicate the possibility of relatively high obduracy.

Second, in obduracy, accumulation leads to lock-in. Lock-in is the difficulty of selecting alternative technologies, organizations, or people once particular outcomes have been established. Arthur (1989) argues that technological artifacts can be locked in as a result of accumulation. In his examples of new technologies competing for adoption, the accumulation from increasing returns inevitably leads to market domination. The winning technology gets locked in.

To generalize beyond the narrow example of positive feedback in a market, lock-in can occur for a multitude of reasons. Influential social groups and proximate decision makers often invest a great deal in any given line of development. Capital invested in technological artifacts contributes of course, but social factors such as the desire to be reelected or the legal requirement to show returns to investors can contribute to lock-in as well. But there are other types of investments. Lock-in can also occur because citizens learn workarounds and learn to use and incorporate a technology into their routine activities. It can seem like such lessons, sometimes learned the hard way, may be for naught if a switch to an alternative is made, making even superior alternatives seem unattractive. Lock-in thus works both on technological artifacts and on political power relations, and locks out other technological artifacts and partisan groups.

Systemic irreversibility and inflexibility can lead to lock-in as well. Inflexibility, especially infrastructure dependence, tends to centralize decision-making (Collingridge 1992). Centralized decision-making inherently reduces potential options by locking out other partisans who might be interested in pursuing alternatives. Irreversibility works similarly. When a single translation of an actor network becomes dominant, that network becomes irreversible (Callon 1990). At some point, competing translations become locked out and only the dominant translation remains as a seemingly viable option, thus becoming locked in. For example, Britain’s high rise public housing is notoriously poor quality, structurally unsound and too permeable to the elements in addition to contributing to undesirable community structures. Given the vast development, construction, and maintenance costs, putting that money towards building traditional houses instead could have housed 40% more families (Collingridge 1992, 124). Had the families been asked, this would have been their preference. But the project was conducted administratively, rather than politically: quantitative housing targets imposed from national bureaucrats led to local authorities to select to build more new housing projects in the form of high rises rather than pursue other solutions (Collingridge 1992, 138–42). Decision-making was highly centralized, with only a handful of national and local officials having any influence over the process.

But obduracy is not limited to artifacts. Social groups can also be locked in and out. Obduracy is not a neutral property of sociotechnical systems, but is political. Sources of obduracy, as described by Hommels (2005), are thus also connected to social groups who are partisan. Improving obdurate sociotechnical systems thus also means navigating the opposition from powerful social groups who erect barriers against the destabilization of obdurate systems. This is implied in Hommels's discussion of dominant frames, but never directly addressed. Such barriers also effect which social groups are included and which are excluded in pertinent decision making. Groups which become routinely included, protected by the barriers to political participation erected through obduracy, become locked in to technological decision making. Those groups which are routinely excluded are locked out.

Continuing the example of reactor development, decisions at the outset of nuclear power development were monopolized by a secure subset of government officials. Potential critics were excluded from the process, and thus nuclear power was overzealously promoted. The focus became one of making practical nuclear power operational quickly at the expense of other considerations (Joseph G. Morone and Woodhouse 1989). In this case both a particular design and a group of decision makers were locked in. But once a particular technological development and social group become locked in they tend to simply accept negative consequences. To avoid such lock-in for spaceflight, this book asks, are particular groups of partisans dictating development of private spaceflight? Are there a variety of options in the event that major errors occur?

Third, obduracy limits the available future pathways for technological development, thus creating a path dependence in which past and present decisions exert a gentle tyranny over the future. The designs of important technological systems, such as streets or manufacturing systems, were decided mostly by people who are long dead, and very few people now have any substantial influence to make them otherwise. Fields like urban planning as well as engineering and design largely train their practitioners to take for granted these inherited systems. The variety of available decisions may be severely constrained by previously made decisions. These constraints may be both real and perceived. Sometimes they are cultural; traditional ways of thinking may prevent some decisions from even being considered (Hommels 2005). Other times they are structural; the patent system, for example, shapes design considerations such that some designs, that would be possible under alternative legal configurations, are not considered (Kranakis 1989). While some degree of path dependency is unavoidable, it nonetheless impairs steering of technological development.

Path dependence has often been described as "history matters," meaning that historical choices influence present and future potentials. Alexis de Tocqueville utilizes path dependency when he theorizes that democratic societies give rise to empiricism and mass production while aristocratic ones lead to theory and unique high quality goods (de Tocqueville 2000). Path dependency also applies to the way contemporary decisions shape future pathways. Kemp et al (2001) argue that "the development of new technology thus depends on characteristics of the existing technological regimes and the overall sociotechnical landscape" (Kemp, Rip, and Schot 2001, 276). Human and organizational components of technological systems also influence available future options. A designer's intellectual community, and the reward structure of professional societies can influence available development pathways (Kranakis 1997). These components circumscribe themselves into the pathway of technological development at the very level of design (Kranakis 1988, 1989).

Kranakis explores path dependency by examining two engineers with the same goal: creating a new suspension bridge design. But they are from culturally distinct nations: the U.S. and France during the early 19th century. The undeveloped American frontier, along with a patent structure and culture which rewarded entrepreneurs, led the American engineer Finley to design a cheap and easy to build bridge using widely available materials so that he could make a profit licensing the design to small frontier towns that needed bridges. The more academically oriented reward structure in France, such as the aristocratic system of professional societies there, rewarded contributions to theory instead. So the French engineer Navier focused on developing new mathematical models for suspension bridge design so that he could advance within the hierarchy of his professional society (Kranakis 1989, 1997). Hommels makes a similar argument in her conception of persistent traditions. In her example she shows how historical factors influence the post WWII development of the U.S. compared to Europe. In the U.S. this development focused on single family homes, reflecting historical American values, while in countries like Sweden and other European nations, multi-family housing dominated post-war development. Historical factors can play significant roles in shaping future trajectories.

Of course all technological development is historically dependent to some degree. Path dependence begins to contribute to obduracy when it prevents adjustment in response to any consequences that may arise as a result of a particular development pathway. Obduracy often creates very real and physical barriers to alternative technological arrangements, but it also places perceptual barriers that are just as difficult to surmount. Are the goals for private spaceflight available for reinterpretation? Does it still seem possible to develop differently?

Fourth, obdurate technological systems have momentum. Thomas Hughes (1969, 1987a, 1994) adapts the concept of momentum from physics as a metaphor which describes the increasing size and influence of technology. Momentum addresses why technological systems seem deterministic when STS scholars have so thoroughly demonstrated the social construction of technology (Bijker, Hughes, and Pinch 1987). Momentum is mass multiplied by velocity. Likewise, technological systems have a mass of technical artifacts, as well as human and organizational components. They have a speed of both technical and organizational innovation and they have a direction or trajectory. The more systemic components and the faster the pace of innovation, the greater the momentum becomes. Technological systems increase their influence over their environment as their momentum increases.

One of Hughes's examples explicating momentum focuses on electric lighting companies. Momentum begins when these companies experience what Hughes calls a "reverse salient," such as when the company wastes electrical generation capacity because they must be able to produce for peak usage, or when short transmission distances require excessive generator plants. To fix these problems, companies may seek a variety of solutions. They may invent new artifacts, such as improved transformers on transmission lines or new generator motors. Or they may seek organizational solutions, such as vertically integrating related services like coal mining, transportation, or equipment manufacturing to ease the financial burden of wasted production capacity. In any of these cases, the utility companies control new technologies, more shipping, more mining, more manufacturing, and require more expertise which in turn requires education oriented towards the company's needs. Other artifacts, organizations, and people become connected with and dependent on the electric power company (Hughes 1994). In this way the repercussions for attempting to alter the operation or function of the power company become increasingly far reaching and impactful, which thus discourages any significant change, even in response to undesired consequences such as pollution. In this way, momentum increases.

Hughes's claim is not that technologies determine social outcomes, of course. Rather, he blurs the distinction between technology and society by analyzing technological systems. Technological systems consist of human, technical, and organizational components all interacting in such a way as to mutually influence and shape one another. Components outside of this mutual influence, those components with only one-way relations of influence or no influence, are part of the environment (Hughes 1987a). Systems with momentum cease to be influenced by their environments, instead exerting influence over them. However, because both technological systems and environment consist of both technical and social components, it is not quite accurate to say that this process describes technological determinism.

Momentum has an important implication for obduracy, which is that systems with large momentum are more difficult to turn from their development path or to replace with alternatives. In this way momentum contributes to obduracy by making it more difficult to steer a system as momentum increases. Momentum gathers as new innovations solve old reverse salients, thus adding components and increasing the pace of innovation in the technological system (Hughes 1987a). Momentum is a clear barrier to reconstruction, and reduces the ability of policy makers to respond to any harmful consequences which may occur.

Nuclear reactor development experienced a great deal of momentum. Innovations were directed towards solutions to problems with established technologies rather than testing alternative ones. For instance, applying light water reactor technology from military to civilian purposes rather than pursuing a variety of potential reactor configurations, or scaling up nuclear power production for large utilities rather than pursuing small reactors for small or co-op utilities (Joseph G. Morone and Woodhouse 1989). What sorts of innovations come about from private spaceflight? Are these innovations supporting a plurality of potential future pathways, or further entrenching existing ideas about what needs to be improved in spaceflight?

Technological decisions can accumulate and gather momentum, locking in pathways for future technological development and locking out dissenters and the alternatives they support. The result is obduracy. Obdurate technological systems seem to develop autonomously and march inevitably forward because of these four facets of obduracy.

Table 2.1: Table defining each facet of obduracy, comparing it to aspects of similar concepts, and providing and illustrative example

Facet of Obduracy	Description	Aspects from Hommels	Aspects from Collingridge	Example
Accumulation	Technologies are formed, not intentionally, but by many events, decisions, and factors over time.	Obduracy builds over time through the addition of new technologies as persistent traditions.	Learning is more difficult if connections between instigating events, factors, and decisions aren't well understood.	Adoption of VHS over Beta. VHS selected because initial decisions compounded despite no intent to select VHS long term.
Lock-in	Some partisans, social groups, or artifacts dominate to the extent that they prevent alternatives from being selected.	Inflexibility can lead to lock-in by centralizing decision-making and hindering the ability to learn about alternatives.	Dominant Frames: Different groups are "closed in" or "closed out" of determining which frameworks dominate.	British public housing development was dominated by high-rises because only bureaucrats were substantively included in decision-making.
Path Dependence	When past and present decisions about development	Dependence on an inflexible technology increases over time	Longstanding cultural norms (persistent traditions) can	Differences in Patent law, professional societies, and other reward systems led to

	prevent adjustment in response to unforeseen consequences.	as it is used.	exclude some options from consideration without appropriate diversity.	different suspension bridge designs in the U.S. and France.
Momentum	A large mass of human, organizational, and technological components is difficult to steer to meet new or persistent development goals.	Entrenchment: Control of one technology requires controlling many others, this is similar to the "mass" of technological system.	As technologies become more interdependent their momentum increases which then can lead to technologies becoming included in Persistent Traditions.	Power companies' innovations add created interdependent relationships between other groups and those companies, making change more difficult.

2.4.1 Obduracy as a Whole

Each of these facets on its own does not produce obduracy. Obduracy as a whole comprises all of them. What is the difference between the whole and its parts? To understand obduracy it is important to understand its facets, but also important to understand that obduracy is a whole concept on its own. What differentiates obduracy from other similar concepts, like those already discussed from Hommels and Collingridge? On what scale of analysis is obduracy most useful? To better understand what obduracy is and does, we must also ask, "what *isn't* obdurate?"

A sociotechnical system has become obdurate when its day-to-day operation reduces the prospects for steering. Such a process does not occur immediately. Obduracy accumulates through a series of often seemingly inconsequential decisions or events. Accumulation results in obduracy in conjunction with other facets. First, obdurate sociotechnical systems become locked in and alternatives become locked out. Social groups who favor the obdurate system lock in their own power, authority, and influence while competing social groups become locked out. Obdurate technosocial systems also create a cycle of path dependence. As the technosocial system becomes more obdurate, it closes down potential options for future decision making. This can occur through a variety of mechanisms, ranging from financial barriers like a desire not to waste high sunk costs, to cognitive barriers such as greater difficulty conceiving of alternative ways of doing things. Obdurate technosocial systems also have a great deal of momentum. As these systems grow in size and the pace at which actors solve reverse salients increases, these systems will begin to influence adjacent systems more than they will be influenced in turn. These factors combine to perpetuate the obduracy of the sociotechnical system, ensuring that steering remains difficult over time. The greater the obduracy, the less the prospect for making alternative choices. Each facet makes it harder to reconstruct technological systems in line with changing values and priorities, and therefore should be minimized.

Obduracy does not mean the same thing as static, fixed, rigid, or any other synonym for unchanging. Hommels equates obduracy to resistance to change (Hommels 2005, 323–24) but here, obduracy means something very much like the casual usage of the word: stubbornly refusing to alter a course of action. As such, obdurate systems might find more appropriate synonyms in stubborn or obstinate; obduracy is a resistance of *influence* over change rather than resistance to change itself. A technological system might change a great deal if its supporters believe that change will thwart an alternative by which they would benefit less.

One problem with defining obduracy as unchanging is that it fails to account for innovation. Innovations can promote the continued use of a particular system while limiting the consideration of alternatives. As unchanging as the urban spaces described by Hommels may seem, innovation still occurs frequently. In recent decades, entire cellular infrastructures have been added to urban spaces. Many of the high-rises in major cities were converted to house large internet servers. What makes these urban spaces obdurate is not that these changes were prevented, they clearly were not. Instead, these innovations were designed to *adapt* to pre-existing urban infrastructure rather than *challenge* them. The obduracy of urban spaces prevented their designers or other interested social groups from having an adequate say in the alternative possible configurations of these technologies, thus preventing more intelligent steering of the changes that were made. When one looks at obduracy not as resistance to change, but as resistance to steering, one might acknowledge that such innovations are common place.

Another example might be driverless cars or solar roadways. While both of these substantial innovations are completely different from current technologies in some senses, both further entrench the technosocial systems of roadways and automobility. Thus, not only is obduracy very compatible with innovation, innovation itself can contribute to the obduracy of technosocial systems.

Another way of helping to clarify what obduracy is and what it means for something to be obdurate might be to provide examples of what isn't obdurate. Obduracy is a useful conceptual tool for technosocial analysis and for better decision making, but it is not a catch all for any kind of inflexibility or entrenchment. One question this dissertation poses is to what extent does private spaceflight seem to exhibit the different facets of obduracy? But what else can be obdurate and what can't?

In a general sense, individual artifacts are not obdurate. For example, Collingridge convincingly shows that the space shuttle is inflexible, but I argue that it is not obdurate, though it may contribute to obduracy. Collingridge shows that the space shuttle required long lead times, its development was very capital intensive, it suffered from large unit sizes such that each shuttle was one quarter of the entire fleet, and it depended upon dedicated infrastructure (Collingridge 1992). These criteria are very well suited for the space shuttle. But the criteria for obduracy are not as well suited to that level of analysis. Accumulation is a useful analytic for the space shuttle. However, far from becoming locked-in, both the military and commercial satellite companies were quick to seek alternatives when the space shuttle did not meet cost or launch frequency expectations. The military needed to have backup launchers because the shuttle lacked the launch frequency to respond to emergency situations (Bromberg 1999a). Commercial satellite companies took a wait-and-see approach rather than redesigning their payloads to take advantage of the shuttle’s new capabilities, seeing early on the potential inflexibility of the shuttle as a launch system (Bromberg 1999a). As such, the shuttle did not prevent organizations from selecting alternatives, it did not dictate future designs, nor did it gain enough momentum to determine its environment.

More generally, the shuttle did not inhibit learning after its retirement. The Space Launch System (SLS) currently in development, rather, shows that NASA learned from the inflexibility of the space shuttle. The SLS has been designed to be semi-reusable rather than fully reusable from the start to reduce capital intensity, and can accommodate a variety of configurations to adapt to different missions so that NASA does not have to discard their launch vehicle if their mission changes (as it often does during presidential transitions) (National Aeronautics and Space Administration 2012, 2016). While it is still large and expensive with long lead times, and almost certainly still inflexible, the SLS exhibits some evidence of learning and of at least increasing built in flexibility compared to the shuttle.

The scale of analysis is also important for obduracy. Obduracy is a concept designed to do analytical work at a broader level. So, while the space shuttle is not obdurate, it could be an integral component in an analysis using obduracy. For example, asking the question "why was the space shuttle so capital intensive?" points to the system of military-industrial contracting that NASA inherited from branches of the armed forces. The aerospace industry was hurting when the space shuttle was developed, so contracts needed to be given out to keep the industry afloat. This required constant spending, even as the design and purpose of the space shuttle remained under debate. Many aerospace companies had merged or gone out of business, leaving a smaller pool of contractors and less competition, and each company had every incentive to maximize the size of their contracts. Such a system for development made the outcome of an inflexible technology distressingly difficult to avoid. Without anyone actively making the decision to keep costs high, the accumulation of day-to-day operations ensured it. Despite the desires of NASA officials to keep costs low, the contracting system locked out the best options for meeting this goal. The broader situation played a determining role in the design of the space shuttle; alternative pathways were limited. So, while the space shuttle was not obdurate, it could still be an integral component in an analysis using obduracy.

Another example of the importance of scale is automobility. On the scale of automobility, obduracy could be a useful tool of analysis, but is not as useful on the scale of individual automobiles. The consequences for the driver of an individual automobile can be described simply in terms of the likelihood that consequence, like an accident or a breakdown, and the severity of that consequence. When the scale of analysis increases to automobility, however, the same analytical concepts are not as helpful. Pollution, long commutes, noisy roads, and divisive highways are all consequences of automobility. Those who suffer from them the worst may now wish that some alternative choices were available which might yield different results. Obduracy promotes questions such as what could have been done to intervene as automobility was cumulatively constructed? What could still be done?

2.5 Conclusion

Obduracy is a broad, macro-level barrier to the ability to alter decisions about sociotechnical development in response to new information. In this chapter I have outlined four facets which identify and contribute to the obduracy of sociotechnical systems. The broadest argument of this chapter is that each of these facets contributes to obduracy as a barrier to re-choosing alternative sociotechnical configurations. The most obdurate sociotechnical systems developed through a process of accumulation, lacking explicit decisions about development which might be challenged or built upon; lock-in of artifacts, organizations, decisions, and actors while simultaneously locking out alternatives and competitors; path dependency binding potential future pathways to past and contemporary decisions and limiting those alternative options which seem feasible; and technological momentum which makes alterations to technological systems more difficult.

Hommels describes obduracy primarily as a resistance to change, and provides three mechanisms by which sociotechnical systems resist change. My conception of obduracy diverges slightly from this, theorizing the ways in which innovation, even rapid innovation, might contribute to obduracy. Obduracy can involve a great deal of change in my conception. What is important is that the trajectory of development is static. For example, accumulation allows an analyst to examine how different modes of change might or might not also result in lock-in or path dependence. And a rapid pace of innovation may increase the momentum of a technological system, or increase lock-in if innovations are made improving one technology while competing technologies receive little attention.

Collingridge's analysis of inflexibility focuses on individual artifacts or sets of artifacts. For example, Collingridge analyses the space shuttle through the lens of the four components of inflexibility which he develops. My conception of obduracy extends this framework to address systemic causes of inflexibility and therefore barriers to increased flexibility. To extend the same example, obduracy would help an analyst answer the question: why did the space shuttle proceed inflexibly?

Obduracy also avoids a binary analysis in which sociotechnical systems are either obdurate or malleable. Views of obduracy ought not be totalizing. That is, obduracy is characterized by varying degrees of each of the facets described in this chapter. I argue that minimizing obduracy is desirable for those who care to allow future generations to make their own technological choices. However, minimizing obduracy could mean minimizing some facets over others or accepting tradeoffs between different facets. Deciding what tradeoffs are acceptable and how much minimization of obduracy is appropriate thus remains a value judgment. I therefore don't believe it is necessary to suppose that avoiding or minimizing obduracy and taking action are opposing categories. Making decisions or steering sociotechnical development in such a way as to leave open the possibility for re-choosing does not mean never committing to a particular pathway for developing. In fact, the routinization of accumulation that goes along with inaction or indecision can actually increase particular facets of obduracy.

In the following chapters I apply the multidimensional concept of obduracy developed here to the analysis of the contemporary privatization of spaceflight. How has accumulation shaped the development of private spaceflight in the United States? How have political arrangements become locked in vis-à-vis the sociotechnical system of spaceflight? How diverse are the potential pathways of space development within private spaceflight? What are the values and goals supported by private spaceflight innovations? Through these analyses I will demonstrate the degree to which private spaceflight shows signs of each facet of obduracy, and suggest alternatives for what less obdurate development of space might look like.

3. Accumulation

3.1 Introduction

The manner of decision-making itself contributes to obduracy. Sometimes, policy decisions are made explicitly in line with a particular policy position. However, policy positions or technological trajectories often result from *many* decisions, actions, or events. It is tempting to view technological decision-making in the former sense. For example, the decision to initiate and follow through with the Apollo program was a discrete decision in line with other cold war policy positions regarding U.S.-Soviet relations. It was thus relatively easy to cancel the Apollo program when it was no longer politically desirable, even if it was harder to establish a replacement. But what about the reverse, when technological decisions, events, and other factors combine to inadvertently create a policy position? A simple example might be the creation of Silicone Valley. Initially, key figures in the electronics industry set up shop in the 1940's and 50's in Santa Clara county due to the proximity of Stanford University. While not all locations might have been useful, certainly many other university towns would have been just as advantageous. But these initial decisions, and whatever factors drove them, led to economies of agglomeration. Local availability of engineers, supplies, components, low costs of transportation, and knowledge spillover between firms made the location obviously advantageous for each of the 900 or so other firms that followed (Arthur 1989). While none of these initial decision-makers intended to create the Silicone Valley known today, it was established by their decisions nonetheless. When decisions accumulate like this, it is more difficult to change them because they lack adequate coordination for learning. The activities and decision-making that contribute to such policies are made routine and therefore less thoughtful. Accumulation is a processes of decision-making that contribute to obduracy.

This chapter analyzes how the historical accumulation of governance mechanisms privileging business interests and market logics influence the ability of decision-makers to alter trajectories in response to learning. Learning is especially important as decisions, events, and factors begin to accumulate because a plethora of variables necessitates a trial and error approach (Woodhouse and Collingridge 1993). It is too difficult for the outcomes of such complex relationships to be predicted, or even accurately guessed. Therefore, to even know if changing space development is desirable, it is important to observe and respond to the accumulating factors. Less thoughtful and more passive approaches risk ignoring factors which are important to change. How has accumulation led to unintended policy positions regarding the private spaceflight sector? What roles did small events, decisions, and factors have in shaping the development of the private spaceflight sector compared to major incidents like the Challenger disaster? How does accumulation towards privatization of spaceflight capabilities work to preclude the consideration of alternatives by NASA officials? What shifts have changed the values of U.S. space program over its history? How is accumulation still at work in the contemporary movement towards privatization?

In this chapter I will present several historical vignettes that analyze the relationship between accumulation and privatization in American spaceflight. These begin with the transition from Apollo to the space shuttle, and continue chronologically to contemporary spaceflight. The goal of this history is not to be comprehensive, but to historically situate the contemporary push for market governance. Contemporary privatization is part of a historical trajectory that has built up to the current policy but need not have done so.

3.2 Characterization of Accumulation

The accumulation of decisions, events, and factors is a necessary component of obdurate sociotechnical systems. Accumulation is one mechanism by which technological development occurs. In any circumstances of increasing returns, accumulation can overshadow deliberate choice in the steering of technological development. Technologies competing in a market often come to dominate not because they are superior, but because of advantages early on; once they have some initial advantage, increased adoption causes the accumulation of further advantages until market domination occurs (Arthur 1989, 1994b). The locations of factories and industries often are the results of accumulation; at the outset, active decisions and contingent factors may increase the density of a particular industry at a particular location after which, other industries coupled to the first through infrastructure will also locate nearby to take better advantage of those connections (Arthur 1986).

Unpredictable circumstances altering initial conditions can cause an accumulation of decisions, events, and factors which provide some real or perceived advantage to a continuation of similar decisions, events, and factors. The result can be a reduction in at least the perception of available paths for technological development, and the lock-in of whatever technological system benefits from accumulation, and thus the lock-out of whatever systems compete against it. This could be as relatively innocuous as the domination of the market by one consumer technology over its competition, or as impactful as the domination of a particular worldview through which decision makers conduct technological governance.

Accumulation limits the possibility for assessment of technological decision-making because it obscures some of the factors which go into directing technological development. It is thus similar in outcome to centralization of decision-making. Although accumulation doesn't necessarily limit who can be a proximate decision maker, it does limit the ways in which decision makers can diverge from the default or status quo position. Lindblom argues that centralized planning, state or otherwise, is necessarily less intelligent than coordination through mutual adjustment, where actors make decisions partly in response to the decisions of other actors, because of the cognitive limitations of having only a few people consider the outcomes of important decisions (Lindblom 1965). Accumulation makes certain outcomes and decisions seem inevitable and therefore leaves others off the table for consideration. Planning is more than just decisions which are made, but also decisions which are not made. The pathways of development which are selected are just as important as those pathways of development which are rejected or ignored. Accumulation draws attention to the ways in which non-decisions also set policies.

At the macro level, the accumulation of decisions, events, and factors look no different than an explicitly staked out policy position, but without the requirement of an actor or group of actors articulating that position. Accumulation, thus, draws attention to the major policy positions that get staked out inadvertently. Accumulation refers to more than just a buildup. For example, suburbia is in the United States is supported by taxes and fees which support roadways rather than other forms of transportation, tax reductions for mortgages, expenses included and not included in mortgage calculations, market incentives which keep urban property expensive and rural property cheap, and the opposition of construction firms, developers, and big-box stores, and a host of other factors (Dotson 2015a). None of these practices seem out of the ordinary, but they result in suburban development without anyone having to decide on that type of development. Such decisions are unintended as a policy, but they are not unintended generally in all of the ways in which interests get represented and in which actors push policy makers towards their positions. Accumulation points to the ways in which obduracy has some affinities *despite* human intentionality. I refer to this as routinization: accumulation often results from actors simply following their routine which, in the process, supports the increasing obduracy of a technological system. Obduracy must be maintained through an accumulated routine, in constant need of reconstruction, but a reconstruction which is largely made invisible by that same routine.

Accumulation works similarly to accretion, layers of bureaucracy and institutionalization pile one atop the other to produce the formation of a policy position. However, accumulation also has direction. Systems accumulate towards something. In the case of residential development, accumulation has been towards suburbanization. In this way, accumulation takes technological development down certain pathways rather than others. So while accumulation builds up in an additive way, it is simultaneously subtractive as it deprives actors of the option to follow alternative pathways and locks them in to a particular policy position that they may not have articulated. Has accumulation in spaceflight built up towards privatization and market governance?

3.3 Competition Determining Design

The idea that the best design for a given technology will emerge through a system of market competition goes unquestioned in much recent political discourse; yet this idea has not always been the norm. The designs used in the various components of the Apollo program were not determined through the market principle of competition. Instead systemic coordination between engineers, administrators, scientists and others determined technical designs before they were contracted. What happened to shift to the now common practice of contractors submitting their independent designs for competition? In what ways did the process of accumulation contribute to this shift, such that the policy was never explicitly staked out?

Before the space shuttle, NASA engineers designed space craft, while the private sectors built these designs. From Mercury through Apollo, NASA's capsule designs all came from the design team at Langley headed by Maxime Faget (*Aviation Week and Space Technology* 1958; Hansen and Administration 1995; Swenson, Grimwood, and Alexander 2010). While NASA competitions for contractors to construct these space craft theoretically allowed design changes, NASA heavily favored "responsive" proposals, or proposals that reflected the NASA designs from Faget's group as closely as possible. Proposals that altered NASA designs were officially referred to as "arrogant" proposals (Bromberg 1999b, 43, 58). By officially labeling industry designs as "arrogant," NASA communicated how little value they placed on industry designs at the time. NASA designs were assessed more favorably, and any industry team who believed they could do better was considered arrogant. Responsive proposals nearly always won (Bromberg 1999b, 43, 58), arrogant ones lost, and industry was quick to learn this pattern.

During Apollo, NASA was operating using an imaginary of the future of spaceflight that was largely envisioned by Wernher von Braun. Von Braun published several magazine articles (Cornelius Ryan 1952), books (Braun 2006 [1948-52]; Braun 1953)[1], worked with German science fiction author Willy Ley (Logan 1953; von Braun, Whipple, and Ley 1953; Ley, von Braun, and Bonestell 1960), and even worked with Disney to publish three television films (Ward Kimball 1955a, 1955b, 1957). In these publications, von Braun envisioned an incremental but steady movement of humans out into space. It began with isolated missions to the Moon, followed by a continuous human presence in orbit, then a continuous presence on the

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[1] *Project MARS: a Technical Tale*, was published piecemeal in various magazines between 1948 and 1952 with the entirety of the book not being published until 2006.

Moon. This presence would build up to isolated missions to Mars, and culminated with continuous human presence on Mars. From there, humanity could continue in this pattern to wherever in the heavens they desired!

While the Apollo program was landing crews on the Moon, NASA was already planning to implement von Braun's vision in their next space program. NASA promoted a program that would: establish Earth and Lunar orbiting space stations, reusable shuttling vehicles to transport crews and cargo off of Earth and between the two stations, and a deep space vehicle for going from these space stations to Mars (Space Task Group 1969). However, while von Braun's progression of space exploration seemed natural to those within NASA at the time, the political situation which had served NASA during the Apollo program no longer existed. Apollo had been given such large political support because it was necessary for winning the space race. Sending humans to the Moon acted primarily as a political signal to so called second world countries demonstrating the technological and military superiority of the U.S. and was an integral part of the response to the domino theory of communist influence. After Apollo, further gains in space would no longer serve to increase the American advantage over the Soviet Union, and so political support for further building up the space program as von Braun envisioned eroded (Launius 2004a, 14).

Other geopolitical changes influenced the success of NASA's proposal. Around the same time as Apollo was wrapping up, Europe was completing its economic recovery from WWII. Having lagged behind the U.S. because of the destruction and death of the war, Europe was now regaining its economic power, and the U.S. was becoming concerned about the prospect of its diminishing economic dominance. Likewise Japan, too, was completing its recovery and proving to dominate in areas such as electronics manufacturing. Economic competition with

Europe and Japan began to reduce the significance of Soviet competition for American politicians (Kloman 1985; Launius 1996).

Several domestic issues also challenged the political climate that had served NASA so well during Apollo. Urban unrest, the civil rights movement, the Vietnam conflict and anti-war movements, an economic downturn, and concerns over the federal budget were exerting increasingly large pressures on the federal government. The political climate was shifting towards interests in domestic interest (Launius 1994). In conjunction with the geopolitical changes, this new political climate challenged the vision of space exploration held by many within NASA.

How did NASA respond to this decrease in political capital? Rather than gain support for their program by appealing to national defense, NASA now had to adhere to market logics and their programs had to support the economic success of the nation and support domestic priorities. Nixon formed the Space Task group in 1969 to examine possible post-Apollo programs, spearheaded by Spiro Agnew, who was a proponent of NASA's major long term goals: setting up a 12 person space station by 1975 using a new orbital vehicle, expanding to a 50 person station by 1980, followed by a lunar orbiting station to support a crewed trip to Mars in the mid-1980s (Space Task Group 1969). The task group suggested three plans: $10 billion for the whole package, $8 billion if the lunar station was dropped, and $5 billion for only the station and the orbiter (Space Task Group 1969). Nixon, however, did not believe that the project was feasible, and forced NASA to reduce the program even beyond the most limited recommendation of the task group: either the station OR the orbiter. NASA leaders wanted the orbiter. They believed that having a reusable launch vehicle and orbiter would reduce costs and support the future construction of a station (Myers 1998). The Office of Management and Budget (OMB), supported by a 1970 RAND study, opposed this decision. They believed that the development costs of a reusable orbiter would drastically offset any cost savings gained by reusability, and that a station would be better supported by traditional expendable boosters (Shaver et al. 1970).

In order for NASA to justify the space shuttle as an important part of the economic success of the country, and to meet the budget requirements imposed on them by the OMB, they would have to fly more frequently to gain the maximum benefit of the shuttle’s reusability. NASA director Fletcher contracted reports from Lockheed and Aerospace, which were combined by Mathematica, showing that reusability reduced the per launch costs, although only with high launch rates (Grey 1979). These launch rates were justified by the logic that low launch cost estimates would drive up demand which would allow for the high launch rates necessary to meet those estimates. But, to fully convince skeptics of the feasibility of high launch rates, NASA needed to get guaranteed payloads. To do this, NASA approached the Department of Defense (DoD) for an agreement to launch all their payloads on the space shuttle (Bromberg 1999b, 90). This would make the shuttle vital to DoD operations, and thus enroll them in marshalling their significant political clout in support of the shuttle, as well as ensure that the shuttle had a full flight manifest to keep costs down.

Just like during Apollo, it was Faget’s design team who created a design for the shuttle called the DC-3. Faget and his team designed for three major problems: atmospheric reentry, design inflexibility leading to delays, cost overruns, and safety compromises, and safe landing capabilities. The DC-3 used a strait wing design to improve the shuttle’s in-atmosphere performance, since reentry was likely to be the most difficult and dangerous part of a shuttle flight (Faget 1970; Bromberg 1999b, 80–85). Such a design would decrease hyper-sonic maneuverability, which would decrease the cross-range (Faget 1970; Bromberg 1999b, 80–85), but would address Faget's concerns. The craft would present the lower surface to the airflow on reentry, with a 60 degree nose high attitude. This would eliminate aerodynamic lift from the wings during reentry, but would allow the vehicle to fly like a plane once it decelerated (Faget 1970). Faget also felt that strait wing designs were the only ones flexible enough for the complexity of rocket design. Because the body-lift and delta-wing designs all relied, to some degree, on lift generated from the body of the craft, changes in weight and balance would require changes to the entire orbiter structure. Such changes are almost inevitable in development, and Faget felt like the overall structure should be designed not to have to change alongside (Faget 1970; Bromberg 1999b, 80–85). He was also worried about the poor low-speed maneuverability of these craft in terms of landing safety (Faget 1970; Bromberg 1999b, 80–85). The strait wing design was the appropriate solution to the problems that Faget and his team emphasized. For some in NASA, it was assumed that, again like Apollo, the shuttle would use Faget's design. At the very least, NASA design teams expected NASA to lead the design of the space shuttle, and contractors to continue to be responsive.

NASA design teams felt confident enough to contest one another's designs, and there was less unity between centers than there had been during Apollo. Members of the Houston Manned Spacecraft Center supported Faget's design, but other centers pushed their own designs (Guilmartin and Mauer 1988a). Reports came out attacking Faget's DC-3 design (Guilmartin and Mauer 1988b), but he commissioned reports of his own which concluded with the promotion of his design (Guilmartin and Mauer 1988a). North American adopted the DC-3 design, not because they were convinced by these reports, but because they had learned from their experience during Apollo that NASA wanted responsive contracts and that Faget's designs were both well respected and influential (Bromberg 1999b). They were, for the time being, rewarded with the contract NASA9-9205 in December 1969 (Logsdon et al. 1995).

Faget's success in his space shuttle design was to be short lived. In order to guarantee military payloads for the shuttle, the DoD required a payload bay 60ft long, a launch capability of 40,000lbs to orbit, and a cross range of 1500 miles after one orbit (Bromberg 1999b). Increasing the payload capacity and bay dimensions meant increasing the total weight of the spacecraft. Increases in weight are exponential in spaceflight, as it requires more fuel, which increases the weight further, and further requires more fuel in a cycle that can quickly get out of control. All of this added launch weight meant much higher heat loads during reentry than NASA had originally intended. A cross range of 1500 miles in a single orbit meant that the space shuttle was now required to redirect itself to land at a destination 1500 miles away from the original intended landing site, and was much higher than NASA needed. This increased the required maneuvering capability from NASA's original plans.

Although the DoD had been willing to negotiate where technically feasible, NASA's position for political bargaining was so poor that they acquiesced to every requirement (Collingridge 1990). This ended Faget's design. The strait wing design of the DC-3 could not withstand the heat loads required to achieve either the maneuverability or the payload requirements of the DoD.

Between the DoD requirements, and the budget, which was limited to $3.2 billion per year total leaving about $1 billion per year for the shuttle, NASA took all strait wing designs off the table, including Faget's DC-3 (Guilmartin and Mauer 1988c; Myers 1998). This time, when contractors were called with shuttle proposals, they could see that NASA's negotiation position with the military was poor, and they nearly all submitted proposals that were "arrogant" and included delta wing configurations which could meet the military guidelines. The end design in 1972 ended up being an amalgamation of industry designs, with nothing remaining of Faget's DC-3 design (Guilmartin and Mauer 1988d). From this point on, competition among contractors to determine design became the norm. The space shuttle marks the entry into an era of private sector design that continues today.

Given the history presented, it was largely irrelevant what most decision-makers thought was best: internal or industry designs. The policy was enacted without explicit decision-making to do so. How might such a policy change have been made more effectively?

The main problem with accumulation in this case is the lack of learning. Decisions made cumulatively often lack effective mechanisms for improvement by learning from previous decisions as well as methods for avoiding existing hazards. In other words, the desired result, in this case a space program that lays a foundation for expansion while simultaneously meeting new budget limitations, is discovered, not chosen (Wildavsky 1988, 2). Morone and Woodhouse (1986) offer a strategy for better learning: establish a policy, observe its effects, correct for errors, observe the effects of those corrections, and correct for errors again. But policymakers cannot use this general method without the knowledge or understanding that a policy has been established. In the case of the space shuttle, because switching to contractor determined designs was not intentional, it is very difficult for policymakers to evaluate the effectiveness of that switch. Piecemeal or unintentional policies are harder to observe in order to correct for errors.

The advantage of the trial and error method described above is that unknowns are broken into smaller more manageable chunks (Wildavsky 1988, 37). It is therefore especially effective when applied to policies which accumulate. Accumulation results in policies which are built up from smaller pieces, and thus some of the work involved in a trial and error strategy is already done. The main difference is perhaps the reflexivity required for learning. What if decision-making mechanisms could be put in place that would make policymakers less susceptible to reactionary accumulation and more level-headed? Perhaps little need change if, rather than allowing policy trajectories to accumulate blindly, they accumulated more deliberately.

The first problem this chapter identifies is that NASA officials and members of the Space Task Group promoted a plan that was poorly adapted to the changing political situation. Several strategies may have alleviated this problem. First, decision-makers simply need to be able to recognize the need to reduce obduracy. Von Braun’s plan had become somewhat stuck within the culture of NASA and its supporters. The ability to recognize that alternatives may have needed to be selected to avoid over commitment to one vision might have engendered some improvement. Such recognition is one of the partisan goals of this dissertation. But what is to stop NASA administrators, interested in pursuing the grandest space program possible, from giving only a cursory look at other options before pushing the one most beneficial for their organization?

Another strategy, then, would have been to diversify interests among decision makers. This was very nearly accomplished, as Nixon Administration, the RAND Corporation study, and the OMB all advised NASA on an alternative policy direction from the space shuttle. However, NASA had no explicit obligation to take these positions into account, and so proposed a policy that began the accumulation which altered who controlled spacecraft designs. So, in addition to diverse sets of interests represented in the decision-making process, those interests need to be vested with relatively equitable decision-making authority. For example, if the OMB had been given authority to participate in the decision, NASA may have selected to develop a space station rather than a space shuttle. The Soviet Union, and later Russia, pursued this path. They gained incremental improvements in knowledge about space station construction and operation using launch technology that remains basically unchanged even at the time of this writing. These incremental improvements occurred on a much smaller budget than NASA's space shuttle as well (Collingridge 1990, 1992). The knowledge they gained through this process proved essential to the development and construction of the International Space Station (ISS). Obliging decision-makers to account for alternative interests, or better yet, including a variety of interest groups in the decision-making process, could decrease unintentional accumulation.

The second problem was the DoD. The DoD had very specific needs for satellite launches that did not necessarily mesh with NASA's goals. In these negotiations, NASA was clearly at a disadvantage. By the time they entered into negotiations with the DoD, NASA was already on the ropes, and needed their assistance. Thus, authority rested primarily with the DoD to make decisions. NASA's situation could have been improved with various forms of assistance. This might have come in many forms, for instance regulations dictating interactions between federal organizations. As it turns out, the DoD was more willing to negotiate requirements than NASA officials believed (Collingridge 1990, 1992), so assistance in the form of negotiating expertise may have been all that was necessary. This example demonstrates the need for assistance to those interest groups with less power and authority in order to maintain a balance between the various interest groups.

The third problem that NASA experienced was that there was little cooperation between design teams. Believing that NASA's role as designer was secure, various design teams competed and undermined one another for the prestige of designing the new space shuttle. History shows that this ended poorly, and had these design teams known in advance that the shuttle design would be determined by industry teams responding to DoD priorities, they might have created a more unified front to promote a design internal to NASA. Of course, making such predictions cannot be counted on. NASA's organizational structures seemed to stifle flexibility in this case. It was far easier for these teams to compete rather than cooperate. Increasing flexibility by, for example, avoiding a winner-take-all system of competition might have aided NASA here. This case reflects the need for a better balance between cooperative decision-making structures and those that promote competition.

This section used the case study of the transition from Apollo to the space shuttle to show how the policy of design competition was staked out inadvertently through accumulation. NASA never explicitly altered their policy preferring responsive proposals. Instead, the accumulation of events such as the economic growth of Europe and Japan, or decisions such as NASA's choice to partner with the DoD, inadvertently set a new policy. In the end, aerospace business leaders following their own interests forced the final change towards competitive design proposals by taking advantage of the accumulation and submitting no responsive proposals for the shuttle design. Importantly, had NASA responded differently at many points in this decision-making process, the outcome could have been different. Far from guaranteed, if NASA had been more attuned to their new political situation, followed the OMB's station-first strategy, or taken a harder line in negotiations with the DoD, the policy outcome could have been substantially different. While NASA administrators may still have thought that soliciting industry designs was prudent, such explicit decision-making likely leaves more room for active consideration of the outcomes. This section not only demonstrates how accumulation can stake out major shifts in policy positions in practice even when they are not directly intended, but also that the process of accumulation leaves open many points of intervention.

3.4 Unexpected Consequences of the Challenger Disaster

One of the most important events contributing to the accumulation towards privatization in the space program was the Challenger disaster. Often history depicts the Challenger disaster as an important turning point in the direction and management of human spaceflight in the U.S. Using accumulation as a historical lens, however, is agnostic to the scale of events. Major events like Challenger accumulate along with less easily identifiable events, such as NASA's poor negotiating position relative to the DoD. Events are weighed somewhat evenly, and more attention is directed towards the accretion of small events and decisions than is usually given to them. What other factors and decisions were relevant to the formation of contemporary space policy that may have been overshadowed by the prominence of the Challenger disaster? Can accumulation in favor of privatization still occur even when events like the Challenger disaster substantially harm some private companies?

The DoD wanted to diversify the launch vehicles they used to lift their payloads into orbit. By 1986, the space shuttle launch manifest was so behind that the DoD believed the delays constituted a threat to national security (Reed 1998). They had been pushing for some time to be able to use private launch vehicles in order to launch payloads on their own schedule. NASA of course resisted this. The DoD had agreed to use the space shuttle and in return NASA had substantially directed the design of the shuttle to meet the DoD's needs. Not only that, but NASA still needed DoD payloads to fill out their manifest and launch frequently enough to keep costs down. Now, it seemed, the DoD was trying to back out of the deal after NASA had become locked-in through the shuttle design.

The Challenger disaster may have provided the catalyst for continued accumulation of privatization, but other forces were already pushing for private sector competition with the shuttle for launches. The DoD wanted to use private launch vehicles instead of the space shuttle. After the disaster the shuttle was grounded for two years while the investigation into the accident was conducted and for engineering changes to the shuttle to be made to improve safety (Logsdon 1998). Congress perceived that DoD payloads were too important to postpone so authorized the DoD to utilize alternative launchers (Reed 1998). This same year, 1986, President Reagan banned NASA from competing for commercial payloads (Bromberg 1999b). The ostensible reason was to avoid risking astronauts lives on a payload that could be lifted just as easily in an un-crewed launch vehicle, although the order was in line with the President's view that the public sector should not be using its resources to out compete private launch vehicles.

NASA administrators had already obstructed efforts to encourage growth in the private launch industry. In 1984, Congress had passed the Commercial Space Launch Act which aimed to encourage the growth of the private expendable launch vehicle (ELV) industry (Akaka 1984). NASA marshaled the advantage of public resources to prioritize support for the space shuttle and ensure that private competitors were priced out. The space shuttle development had been so capital intensive that NASA needed to spread those costs out over as many launches as possible to maintain the shuttle's viability. They could not afford competition from private ELVs. To create a successful ELV program, use of the shuttle had to be curtailed. So, though the safety of the shuttle was legitimately in question, it was far from the only reason for banning the shuttle from launching commercial payloads. These factors may have ultimately prevailed even without the Challenger tragedy, as the shuttle's business case proved increasingly difficult to close. The Challenger tragedy may have been the tipping point, but private competition with the shuttle for launches was the result of an accumulation of other factors, such as eliminating the shuttle's monopoly over all government payloads, and preventing government competition over private payloads.

Although the Challenger disaster catalyzed further accumulation towards privatization, privatization can actually foreclose some options that were opened through the private sector itself. Business leaders have a very particular set of incentives guiding their decisions such as profit making, benefitting investors, and business expansion. Decision makers in other sectors will have other incentives and their cooperation and competition can create a diversity of incentives that potentially benefits a broad set of interests and partisans. Privatization, therefore, is a shift in governance from a balance between these diverse interests to a governance structure where the values and interests of business leaders dominate decision-making. Such a process is not necessarily good for all areas of industry, and does not have to correspond with industry success. For example, the focus on the private *launch* industry came at the expense of an entire industry of companies which provided complementary services to the shuttle, such as secondary boosters to allow shuttle payloads to reach geosynchronous orbit. As the market for shuttle launches decreased, many of these companies could not survive. Transpace Carriers, Inc. (TCI) was attempting to purchase Delta launchers to serve as backups for the shuttle. But with a potential market for commercial launches emerging, McDonnell Douglas, the original manufacturer of Delta launchers, decided they would sell launchers directly. TCI declared bankruptcy by the end of 1986 (Bromberg 1999b, 153–54). Astrotech International was forced to sell their space shuttle processing branch, Astrotech Space Operations, to Westinghouse’s Wespace subsidiary because they lacked the capital to maintain the company until the space shuttle resumed launches (Bromberg 1999b, 154–55). Orbital Science had organized their business around providing an additional stage to the shuttle, the transfer orbit stage (TOS). But with the shuttle grounded, they had to adapt the TOS as a small launcher for DARPA research payloads (Bromberg 1999b, 155–56). Private companies responding to publicly driven goals and values within the space program provided a plethora spaceflight options otherwise unavailable. The reduction in the diversity of private options as a result of increasing accumulation of privatization indicates that, while private industry can successfully diversify the potential pathways for space development, *privatization* can, in turn, foreclose those same options.

NASA had also been using their claims to routine access to orbital space via the space shuttle to encourage a space manufacturing market. The Challenger disaster reduced the confidence in the space shuttle, delays reduced the available shuttle launches, and the loss of payloads to ELVs decreased total launches which increased the cost per launch on the shuttle. These factors combined to eliminate any chance of success for a space manufacturing market. In particular, a somewhat promising agreement between NASA and Ortho Pharmaceuticals to manufacture erythropoietin, a hormone used in the treatment of anemia, was cancelled (*Aviation Week and Space Technology* 1986). This development relied on zero gravity testing and manufacturing techniques, which were becoming too infrequent and expensive to compete with terrestrially developed alternatives.

The failure of such space based applications also hurt another emerging space industry. Between 1983 and 1986, Fairchild Space and Electrics Company, as well as Space Industries both pursued shuttle based free-floating platforms (basically un-crewed space station) to lease to NASA and potential space manufacturers (Bromberg 1999b, 163–65). But with no applications, there was no one to lease these platforms, and no viable business model for investors (*Space Business News* 1988; *Aerospace Daily* 1989). Additionally the major space launch companies had been against this line of commercialization from the start. They knew that congress favored an un-crewed approach and that they would not approve a NASA space station if commercial orbital platforms proved successful. The major launch companies wanted a space station because they were expecting to get major contracts from its development and construction, just like they had with the space shuttle (*1989 NASA Authorization* 1988). The increasing influence these companies had accumulated through the EELV program and as the DoD attempted to promote space shuttle alternatives enabled them to block the alternative of free-floating platforms.

How might learning have been improved to reduce the consequences of accumulation in the case of the Challenger disaster?

High levels of interdependence such as those experienced with the space shuttle make learning through trial and error more difficult. In the case of the space shuttle, NASA, the DoD, and a plurality of private spaceflight enterprises depended on the uninterrupted operation of the shuttle for access to space. This created two-fold problems. First, this interdependence incentivized trial without error rather than learning from errors (Wildavsky 1988). Second, it increased the severity or errors, again, incentivizing actors against learning and towards risk avoidance. Thus, when the shuttle was grounded after the Challenger disaster, many of the actors dependent on the shuttle were put in a poor position, and when the shuttle lost payloads in response, it too was put in a precarious position. Such situations of interdependence should be avoided to reduce accumulation and obduracy. Had the shuttle not needed so many payloads to keep costs down, the loss of payloads would not have weakened NASA's position so substantially. Alternatively, had the DoD not designed satellites that could only be launched on the shuttle, they would not have been so incentivized to abandon the shuttle, as slips in its schedule would not have been so costly. Designers should focus on building in substantial flexibility.

Accumulation can also prevent learning by denying the inclusion of interested actors. For example, the DoD was included in negotiations over the design but other satellite companies, which NASA hoped to court to increase payloads, were not. Because the policy for the space shuttle's design was established cumulatively, there was little possibility for NASA administrators to actively consider which actors would benefit the shuttle by providing input on its design. However, by the time these problems presented themselves, it was far too late to change the shuttle's design. Deliberations and consideration of the various interests of all concerned actors should have started far sooner, and more groups should have been included. Had the satellite companies NASA hoped to launch payloads for been included in the negotiations over design as the DoD had, they might have objected to the size of the payload bay as being unnecessary and an added expense. At any rate, as things were, they never got the opportunity.

Although the Challenger disaster was an undeniably important event in the development of spaceflight, conferring too much influence can obscure other important factors. The DoD wanted more control over the launch schedule of defense payloads, and the Reagan administration was prioritizing their policy of privatization. The shuttle was simply not performing as expected, and promises of cheap and routine spaceflight were not manifesting. Private companies who stood to benefit from the development of EELVs supported ceding shuttle functions to private launch companies as well. Perhaps surprisingly, those private companies which had been heralded as the future of commercial spaceflight and had situated themselves as complementary services to the space shuttle were sacrificed. The accumulation towards privatization did not require a general support of private aerospace companies.

3.5 Increasing Privatization in the 90s

Just as in previous decades, the 1990s saw the continued accumulation of privatization. NASA faced two major crises in this decade. First, their funding levels were reduced after a relatively stable funding period. Second, the aerospace industry was undergoing a tumultuous time as well. The accumulation of industry influence over the previous decades ensured that privatization was on the agenda as a possible strategy for dealing with both of these issues. How did the weakening of the aerospace industry contribute to the accumulation of privatization? What effects did the continued accumulation of market governance have on the space program?

As has been shown with the increasing influence of the established launch industry over emerging shuttle services in the 1980s, privatization can come hand in hand with a diminishing industry. The budgets of many federal agencies and administrations were tightened in response to the deficits incurred after the Reagan and Bush administrations. This included NASA and defense contracts. As a result, many of the aerospace companies, even those which had been major military contractors, were no longer financially viable. Large companies responded either by buying smaller companies to try to absorb their contracts, selling their aerospace divisions, or merging. Some companies simply went out of business. General Electric, Rockwell International, and General Dynamics all sold their aerospace holdings. Lockheed and Martin Marietta combined to become Lockheed Martin and Boeing absorbed McDonnell Douglas.[2]

From the standpoint of NASA, a shrinking industry meant a much smaller pool of contractors for competitions. The problem was similar to what Collingridge might describe as a

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[2] Bromberg 1999 provides a very useful visual timeline of U.S. space companies on pp. 12-13.

large unit size (Collingridge 1992). Even at the peak of Apollo funding, NASA did not have the funding or facilities to conduct the space program entirely internally, with no contractors. Alternatives to the reduced pool of private contractors seemed absent. With so few companies remaining, NASA could only expect to get one company biding on any given project (Eisele 1997a). If no companies bid on a project, that project could not proceed. In addition, NASA had already conceded capabilities to private companies, such as the already discussed shift to industry designs and the use of EELV's to launch payloads. Furthermore, many critical activities which NASA could not allow to fail relied on private contractors (Byerly 1992, 270). For example, Boeing declined to bid on a $6 billion dollar contract turning over many spaceflight operations, including human spaceflight mission control centers, to the only bidder: Lockheed Martin (Eisele 1997b; Heimerdinger 2001). Thus NASA awarded a Consolidated Space Operations Contract to Lockheed Martin's Space Operations Team because mission control was a critical operation, and they had no other option within the framework of privatization. Each company became extremely important to NASA's operations, and NASA gained a vested interest in protecting those companies that remained in order to also protect the capabilities they relied on from the private sector. Such increased reliance thus gave industry leaders increased influence.

Although privatization efforts continued unabated, federal agencies were still the main sources of industry profit. Because the government was 90% of the market, privatization was not "anything more than an alternative form of contracting…The aerospace companies simply had more control over design, testing, manufacturing, and quality" (Bromberg 1999b, 161). The main difference between traditional contracting and privatization was the increased influence industry actors and market values had over spaceflight governance and decision-making.

While NASA's budget had been reduced after Apollo, it had been kept relatively stable since 1974, and had even increased from 1988 to 1991 during the Presidency of Bush Sr. despite numerous political and existential threats to the organization. But early into the 1990s, Congress decreased NASA's budget. Thus, NASA was facing the prospect of making some very hard choices about which missions and which capabilities they would have to cut. One strategy was for NASA to cannibalize the budgets of most of their missions to fund only those that they deemed most important. But that meant choosing those few missions that really mattered, and risked angering and disenfranchising huge portions of NASA employees and members of congress who supported work being done on these missions within their districts. Large scale public comments, town halls, or other citizen assessment mechanisms might have helped NASA to pursue this option.

The other alternative was to force their missions to operate on a smaller budget. This second option had its own hazards. It would require a lot of creativity to think of ways to accomplish the same goals for less money. NASA selected this option, and utilized privatization strategies to pursue it. The strategy of using the private sector relied on two things. First, the perceived rule that markets increased efficiency over state agencies. Second, the creation of new markets so that private companies could make a profit without relying on government contracts. NASA would privatize some functions, and proceed with cost sharing programs where privatization wasn't an option.

NASA utilized this strategy of privatization in an attempt to decrease costs on several programs, the largest of which were the development programs for shuttle replacement: X-33 and X-34 reusable launch vehicles (RLVs). In both of these projects, NASA partnered with private companies in a cost sharing model that would leave the private partner with ownership of the vehicles at the conclusion of the project (Amatore and Humphrey 1999; Launius 2004a; Aeronautics and Space Engineering Board 2012). The LightSAR project was an experimental project to use radar, rather than optical or infrared, frequencies for remote sensing. As part of this project, NASA attempted to get 50% financing from private industry and to support modifications of commercial small satellite launchers so that NASA could purchase launch vehicles from private companies rather than use their own (Ferster 1996a, 1996b). The Lunar Prospector mission, a lunar mapping satellite, cut costs by reducing NASA oversight of contractors, thereby increasing management responsibilities for the contractors while decreasing management responsibilities of NASA centers (L. David 1996). NASA also began letting private companies "into the processing of data from the environmental monitoring satellite system" (Bromberg 1999b, 186). NASA leaders had hoped, through these cost sharing programs and programs ceding certain operations to the private sector, that they could minimize the impact of budget cuts on their programs.

Although to NASA, privatization seemed like the only way to reduce costs, it was, of course, only the option that *seemed* most tenable. The historical accumulation of privatization that had already occurred had made private companies NASA's go-to allies. The available pathways by which NASA might have proceeded had already been restricted; NASA administrators did not ask, "what other approaches might work?" (Byerly 1992, 270). NASA continued to use the strategy of privatization which had accumulated as the standard response to their budgetary crisis and to the crisis within the aerospace industry.

Learning by trial and error requires an active approach. It can be difficult, once a strategy becomes routine, to alter it in response to new circumstances. One of the issues this chapter presents is that privatization strategies had become routine by the 1990s. Implementing effective trial and error learning thus requires strategies to overcome the barrier of routinization which is part of accumulation.

Rather than allow policies to passively accumulate, NASA administrators and other decision-makers might implement policies which incentivize constant consideration of potential alternatives. I borrow from Pielke (2007) the idea of the honest broker of policy alternatives to suggest that expertise be utilized not in an advisory capacity but specifically to enhance the number of alternatives under consideration. For example, if NASA were to solicit advice from the scientific community on whether to cut some missions in favor of others, or to rely on private industry to cut costs and maintain as many missions as possible, scientists are likely to suggest the latter in the hopes that the mission supporting their own research is saved. However, utilizing these same interests, if NASA were to pose the choice as being between cutting missions or suggesting some alternative, I suspect those same groups of scientists would provide no end of creative ideas in order to save their missions.

The strategy of privatization dominated among NASA decision-makers and coupled with the shrinking aerospace industry to produce substantial centralization. By this point accumulation had already erected substantial barriers to alternatives, but further accumulation could have been prevented by pursuing multiple strategies for the purpose of trial and error, and reducing the scales of privatization to reduce the potential costs of errors. Instead, centralization necessitated trial without error (Wildavsky 1988), proceeding without the flexibility to accommodate errors. As we have seen, however, errors are often beyond the control of even the cleverest experts.

For example, NASA's bid to privatize mission control proceeded with such a trial without error framework. Could NASA instead have utilized strategies to reduce the severity of errors? Woodhouse and Collingridge (1993) suggest gradually phasing in a new policy to present increased opportunities for learning and conducting simultaneous trials of multiple alternative approaches (Woodhouse and Collingridge 1993, 143). Starting with a massive $6 billion contract for mission control could hardly be described as "phasing in," and awarding the entire contract to Lockheed Martin on the basis of there being no other competitors is certainly not a "trial." Perhaps NASA could have offered multiple smaller contracts for various aspects of personnel management, or for different departments while leaving other areas unchanged to better ascertain the benefits of various strategies. Such an approach would have allowed NASA to support multiple contractors during a lean time in the aerospace industry, have made at least some of the contracts more accessible to more companies, allowed NASA to change or drop contractors with minimal cost or consequences, and provided more information more quickly about the costs and benefits of multiple strategies. Now NASA is not likely to switch contractors that a single company has decades of experience. And what would they do if Lockheed now suddenly declined to renew this contract?

This section has outlined a case in which the weakening of the aerospace industry in the United States actually contributed to strengthening the reliance on privatization and market governance. The mergers and bankruptcies in the aerospace industry left NASA with almost no negotiating power over contracting companies. In conjunction with the privatization practices that had already been established, NASA increased reliance on private companies and market values as strategies to deal with a shrinking budget. Through continued increases in privatization strategies, especially in critical activities, private companies increased their incorporation into the NASA bureaucracy as well as their influence over NASA's agenda.

3.6 Space Shuttle Privatization

The accumulation of technological decision making is quite powerful. As demonstrated in the previous sections, the accumulation of events, decisions, and other factors staked out a policy position for NASA without any need of actors or social groups to do so explicitly. The logic of economy came to dominate decision making for NASA through such accumulation. Two attempts were made to have private companies take over the operation of the space shuttle. The first failed completely, while the second was successful. Given the primacy of the space shuttle in the public mind, and large percentage of NASA’s budget which went to space shuttle operations, this particular move was a substantial one. Why did the first attempt fail? What happened between the first attempt and the second attempt to change the outcome? What does the comparison of these two events indicate about the extent of the accumulation of market governance in between?

3.6.1 First Attempt

The space shuttle became operational in 1981, and was nearly immediately followed by plans for privatization. In 1982, Space Transportation Company (SpaceTran) attempted to partially privatize shuttle operations by purchasing a fifth space shuttle that they would own and NASA would operate (Bromberg 1999b). NASA only had plans for four shuttle orbiters, but SpaceTran founder, Klaus Heiss, believed that this was too few. With only four shuttles there would be no time to make the gradual improvements facilitated by continuous production because production facilities would be closed by 1985, when all four shuttles were to be completed (Heiss 1986). This also meant that replacement parts would be expensive and difficult to produce, increasing the cost of the maintenance of the shuttle. His thought was that adding an extra shuttle would increase the duration of production and the demand for spare parts enough that production facilities could remain open and the shuttle could be more gradually and less expensively improved.

However, several factors worked against him. First, he would have to raise the $1 billion it would take to build a new shuttle (Heiss 1986), an inflexibly high initial cost. When he went to investors, they wanted assurances that even if the shuttle wasn't operational, that payloads would still go up. This meant that he had to contract for backup launchers, a role Heiss proposed would be filled by Martin Marietta's Titan launcher (*Aviation Week and Space Technology* 1982a). But NASA was against this plan. NASA administrators feared that contracting for backup launchers would undercut the shuttle. It would create a competing launcher for commercial payloads, and would tempt the military to continue to use Titan launchers for their payloads rather than use the shuttle exclusively as they had agreed (Heiss 1986). SpaceTran was in a catch 22 in which to get investors to agree to fund the venture they would need to support the Titan launcher which would compete against the shuttle. But to get NASA to agree to the deal, they could not support the Titan launcher because it would compete with the shuttle. Additionally, NASA was concerned that while SpaceTran would net an estimated $300 million per year, NASA would get little in return (*Aviation Week and Space Technology* 1982b). The nail was hammered into the coffin when the estimated price for constructing a shuttle increased from $1 billion to $2.3 billion, an amount Heiss could not even hope to raise. Negotiations for this attempt at privatization ended in 1984 with no new shuttle.

Shortly after, in 1984, Willard Rockwell of Astrotech proposed the outright purchase of two shuttles immediately, one existing launcher and one to be built as a fifth launcher (*Aviation Week and Space Technology* 1984; Saporito 1985). These negotiations also failed for many of the same reasons. From NASA's perspective, privatization removed the core of their human space program from their control. Importantly, this might prevent NASA from steering the shuttle to become the basis for a space station, which was their greater goal at this time. Additionally, NASA didn't see any alternative benefit that they would accrue from making such a sacrifice. But, like SpaceTran, Astrotech did not even get the chance to address this barrier, because they were unable to raise the funds to meet their end of the proposal as space shuttle costs continued to go up (Bromberg 1999b, 137).

One factor undercutting both attempts at privatization was that the aerospace industry was generally uninterested in privatizing the shuttle. SpaceTran and Astrotech were exceptions because their primary interest was not to profit from owning and operating shuttles. Although they would not have proposed privatization if they didn't think they would profit, they were primarily interested in the benefits to flexibility that partial privatization would engender. Adding a fifth orbiter would decrease unit size, and keeping open production lines would decrease unit costs. They believed that partial privatization of the shuttle fleet would support NASA's broader goals of maintaining a permanent human presence is space by reducing costs through reusability (Bromberg 1999b, 137). Other firms that were not so personally interested in the success of the shuttle were uninterested, so no firms large enough and with enough free capital proposed purchasing any shuttles for private ownership. Additionally, investors were more interested in profits than the strength of the U.S. human spaceflight program, and were hesitant to risk so much money when their returns would be so uncertain.

3.6.2 Second Attempt

Although the first proposals to privatize the shuttle failed in part because NASA saw privatization as a barrier to the eventual construction of a space station, NASA supported the second privatization attempt. The space shuttle had been part of NASA's plan since the end of

Apollo. The strategy of privatization had, after the many public-private partnership programs in the 80s and 90s, become normalized as the standard way to achieve spaceflight goals with a shrinking budget. NASA officials continued the use of this strategy to get congressional support for a space station. The previous plan for the space station had NASA acting as its own prime contractor, giving substantial autonomy to individual centers to allocate tasks and subcontracts. However, because the centers were hardly unified in their vision of or goals for the space station, substantial resources had to be dedicated to communication and coordination between centers. The primary strategy for reducing the cost of the space station was a privatization strategy: making Boeing the primary contractor rather than NASA (*1991 NASA Authorization* 1990). This also enabled NASA to eliminate all of the middle management positions running the coordination tasks that were necessary when NASA was its own prime contractor. NASA B-level management for the station dropped from 3000 to 1300 positions (Bromberg 1999b, 180).

The other largest source of costs came from the shuttle itself. The shuttle was an essential component in the construction of a space station, but its operating costs in 1991 had been $4.3 billion, nearly 1/3 of NASA's budget. The situation was made dire when, in 1995, President Clinton directed NASA to reduce spending by $5 billion by the year 2000 (*Aerospace Daily* 1996). Between the accumulation of privatization, the need to reduce shuttle costs to promote the space station, and the decreased spending limit, NASA, again, used the strategy of transferring management to private companies. Lockheed Martin and Rockwell proposed a joint venture to take over management of shuttle operations and took over the shuttle program in 1996 as United Space Alliance (Harwood 1995, 1996). Unlike the prior decade, accumulating events had changed the spaceflight landscape dramatically. Whereas before NASA was unwilling to cede control of their core human spaceflight program, now they had actively solicited privatization proposals. Whereas previously no large aerospace companies had been willing to take over the shuttle, this time multiple firms showed interest such that the privatization came in the form of a joint venture. Accumulation had made privatization seem like a more obvious solution compared to other alternatives, whereas just a decade before it had seemed undesirable and untenable, at least to this degree.

Over fifteen years of space shuttle operation, there was considerable accumulation towards privatization within the space program. This can be seen by examining the differences in attempts to privatize the space shuttle. In 1982 even partial privatization which was directly aiming to improve the flexibility of the space shuttle was rejected by NASA in order to maintain their dwindling autonomy over the direction of space development. But by 1996, NASA was actively courting private companies to operate all four of the space shuttles. NASA had already consistently chosen to cede that autonomy to market mechanisms as a way of coping with increasingly tight budget restrictions and an increasingly difficult political context, so this decision had become routine. The accumulation towards privatization turned the sale of the space shuttle from an unacceptable policy to one that was actively pursued.

3.7 Contemporary Privatization

Given the historical analysis already presented in this chapter, it would be no surprise to find that contemporary privatization is cumulative. What were the events, decisions, and factors that led to this build up? How did it build off of the already existing accumulation of privatization? How could it have been done differently?

Although privatization was becoming increasingly common as a budgetary and managerial strategy in the 1990s, once George W. Bush took office, he created a space policy called the Vision for Space Exploration (VSE), which was the basis for the development of the

Constellation program (National Aeronautics and Space Administration 2004). The advisors that worked on the VSE had originally intended to build off of the privatization of the 1990s. The idea was that NASA should focus their human spaceflight program exclusively on exploration, while those activities in low Earth orbit (LEO) which might be done routinely or cheaply should be conducted by private companies (Alan J. Lindenmoyer 2012). However, NASA underwent a change of leadership and commissioned a new study (ESAS) between the VSE and Constellation, and the Constellation program was more a reflection of Bush Sr.'s Space Exploration Initiative (SEI) which called for a human return to the Moon for long term occupation as the first step to a mission to Mars ("NASA's Exploration Systems Architecture Study" 2005; Connolly 2006).

Even while Constellation was a shift back towards a more government run space program, many aspects of privatization which had accumulated had become obdurate enough that they were incorporated in the contracting process almost naturally[3]. The intention that commercial companies take over LEO was maintained in the Commercial Orbital Transportation Services (COTS) program. COTS utilizes Space Act Agreements (SAAs) instead of cost-plus contracts to seed money to commercial providers for the development of launch vehicles to transport supplies to and from the ISS. Cost-plus contracts entitle the contractor the cost of the contract plus an additional profit for the company and the vehicle belongs to NASA after its development. SAAs pay seed money based on the completion of certain milestone achievements and the launch vehicle is owned by the company with NASA purchasing services. Another important distinction is the cost-plus contracts allow NASA to enact direct oversight over the process, whereas SAAs only allow NASA to enact oversight via the giving or withholding of funds (Alan

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[3] In particular contractors competing over whose design to use rather than who to develop NASA's design.

J. Lindenmoyer 2012). In other words, NASA is much more intimately involved in directing contractors to achieve specific requirements in cost-plus contracts, but commercial companies are left alone when funded through SAAs and NASA only provides general capabilities and only withholds funds if the commercial project no longer seems like it might align with NASA's needs as a future consumer.

While the architects of the VSE had wanted to extend this model to human spaceflight, Administrator Griffin believed that commercial human spaceflight might endanger the funding for the Constellation program (Alan J. Lindenmoyer 2012). Constellation called for the design and construction of two new launch vehicles, the Ares I and V, a crew capsule, the Orion, and a lunar lander, the Altair (Connolly 2006). Griffin was afraid that funding for new launchers would be canceled if law makers believed that commercial launchers could do the same job.

However, Constellation was cancelled in 2010 (Bolden and Holdren 2010)[4]. This created a problem in that the space shuttle was still scheduled to retire in 2010, but it would be several years until NASA could develop any replacement, even if they continued with the Orion space capsule. Building on the already existing COTS program, and the continued momentum from the development programs of the 1990s, privatization was, again, suggested as the appropriate mechanism for solving the problem of the spaceflight "gap" without needing the increased budget that had been the impetus for cancelling Constellation in the first place (Augustine et al. 2009)[5]. Using the same milestone based funding as COTS, NASA began the Commercial Crew Development (CCDev) program. This was shortly combined with the COTS program in a single

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[4] Many components of Constellation, however, were forced through by members of Congress who relied on it for jobs in their districts. Namely, the Ares I and V launch vehicles were redesigned as a single modular launch vehicle called the Space Launch System (SLS), and the Orion spacecraft was kept as an emergency crew retrieval craft for the ISS after the retirement of the shuttle.

[5] It could be argued that the spaceflight "gap" as a concept was, itself, created in order to promote a return to more commercial friendly space policies, but this has no direct bearing on the feasibility of the argument presented here.

office, the Commercial Crew and Cargo Program Office (C3PO). At this point a bureaucratic organization had now been created, but not from any single articulation of a policy of privatization. This created the foundation establishing the track record for other programs supporting private interests, such as the Asteroid Redirect Mission (ARM) and the Bigelow Expandable Activity Module (BEAM) mission to the ISS. Through this build up of commercial activity following the Constellation program, the U.S. now has what could easily be consider a policy of privatization for spaceflight, without such a program ever being laid out directly in a single articulation of policy. Instead, it accumulated through several events, decisions, and factors over a long history of such accumulation.

Again, accumulation has been the primary mechanism for policy development within the American space program. The whole of the project of privatization throughout the history of spaceflight and including recent events can be categorized by accumulation and especially without thoughtful and deliberate choice, a description termed by Winner as “technological somnambulism” (Winner 1977). Woodhouse (2013, 64) discusses democratic ways of addressing such deliberative shortcomings. Where policy makers sacrifice breadth and intensity of deliberation, they also exclude many affected interests. Such exclusion reduces the intelligence of decisions because it allows proponents to avoid challenges and criticism at moments when such acts would be highly productive (Woodhouse 2013, 65). By fostering ongoing deliberation between actors of a variety of interests, spaceflight policymakers could head off this somnambulism, which is one of the most profound consequences of accumulation.

Considering the problem of the spaceflight gap, the ostensibly driving force behind the contemporary push towards privatization, this section has demonstrated that the accumulation of events, decisions, and factors played a major role in the lead up to his problem. Had NASA started preparing more productively for the retirement of the space shuttle earlier and had they not relied solely on the Constellation program the problem that justified privatization would not have existed. What interests were included in the decision-making process that led to this result? Presidential advisors already interested in continued privatization and NASA leadership interested in recreating the grand plans of the SEI seemed to compete over the future of the space program in relative isolation. Would a representative sample of the broader American citizenry have supported a massive expenditure to develop new launch vehicles? Would they have supported continuing to sink money into privatization programs that had been showing marginal returns for over a decade? It could still be possible that a broader more inclusive deliberation would have resulted in similar policy decisions, on the face of it, but such a process would be much more amenable to trial and error learning rather than to accumulation.

3.8 Conclusion

This chapter has covered substantial ground in the history of spaceflight, focusing specifically on the ways in which market influences and private interests have accumulated in the governance of spaceflight. The development of privatization follows the pattern of accumulation laid out in the beginning of the chapter. Ceding responsibilities such as program management and design has become a common strategy for NASA when the administration is faced with barriers, especially financial ones. Such strategies began early and therefore gained relative advantages over alternative coping mechanisms. As the strategy of privatization became more common, it pushed out alternatives. However, this exclusion of alternatives occurred without explicit consideration. It may be that in many of the instances discussed in this chapter, privatization was not the best option given NASA’s goals. Importantly, because alternatives haven’t been adequately explored, it is impossible to know whether other options would have been superior, which in turn means that future assessment of options will be hampered. Privatization is thus a policy position that has not been staked out explicitly, but through accumulation of events, decisions, and factors.

This chapter focused on a series of historical cases in spaceflight to demonstrate that policy positions occurred through accumulation rather than explicit consideration. How did the relationship between NASA and private industry change over time? What events, decisions, and other factors contributed to these changes? To what extent were these changes, or their contributing factors, the result of explicit negotiations over policy positions? This chapter has used these research questions to guide the inquiry for each historical case.

To answer these questions, this chapter considers a long series of events, decisions, and factors which have accumulated throughout the history of the American space program. During the transition between the Apollo program and the development of the space shuttle, NASA shifted from characterizing industry led designs as "arrogant" to determining designs through industry competition. Rather than initiate this policy in response to organizational goals, it was the result of a series of events and decisions, such as NASA's agreement with the DoD in response to political opposition and funding constraints, and the resulting constraints the DoD placed on shuttle design. This accumulation continued into the 1980's as presidential support of privatization and the DoD's desire to use alternatives to the space shuttle were catalyzed by the Challenger disaster to undermine the space shuttle in favor of privately owned launch vehicles. This trend continued in the 1990s as a shrinking aerospace industry meant that each remaining contractor increased their influence and NASA responded to shrinking budgets by ceding management authority to private contractors and initiating public-private cost sharing programs. The extent of this change over time is exemplified by the differences between the two attempts to privatize the space shuttle. Between 1982, when the first failed attempt to privatize the space shuttle began, and 1996, the process of accumulation had normalized privatization enough to change the outcome. This same normalization through accumulation contributed to the contemporary policy of privatization.

That privatization comes about through accumulation in the case of spaceflight does not mean that interested actors do not exert a concerted effort to obtain particular outcomes. In fact, part of the reason that accumulation may occur, why particular sociotechnical strategies for problem solving may become routinized, or why certain conceptions of problems become dominant, is the effort of powerful social groups with common interests. For example, while it took a substantial set of other factors, it was certainly in the interests of industry contractors to determine the design of the space shuttle rather than through a process internal to NASA. Accumulation is only one of many factors that contributes to obduracy. The following chapter will examine how the lock-in of such interests, as well as other components of sociotechnical systems, also contributes to increasing obduracy.

4. Lock-in, Lock-out

4.1 Introduction

Decision-makers can become reliant on the particular interests of one social group, the technical capabilities of one artifact, or the decisions made by one set of actors. For example, if you utilize the hunt-and-peck method of typing, you might wonder why qwerty keyboards have a such a nonsensical layout. Even if you are an accomplished touch typist, you may be familiar with the more efficient alternative layouts, such as the Dvorak simplified keyboard. The qwerty keyboard became dominant because, as an early keyboard layout, it was the first for which an efficient touch typing method was developed (P. A. David 1985, 334). This gave it a major advantage in adoption and the more it was adopted the greater the advantages were in using it. It remains universal today despite multiple, well known, and more efficient layouts existing for over 100 years. With executives making most of the corporate purchasing decisions for keyboards, tying speeds are secondary to factors like price, ease of finding a supplier, and number of already trained typists. It is not surprising that we are now locked in to the qwerty keyboard, despite obvious superior options and perhaps our own preferences.

The previous chapter focused on accumulation: how better learning about technology for better technological decision-making is hampered by a systemic lack of attention. This chapter tackles a different facet of obduracy: how learning too late can render that learning irrelevant: lock-in. Lock-in can have consequences more serious than slightly slow typing. Reliance on the space shuttle affected numerous other aspects of spaceflight: delays caused massive perturbations in launch schedules and had extreme impacts on national defense and satellite industries. Lock-in reduces the prospects for alternatives, and makes improvement of current options more difficult as well. Lock-in attends to how various forms of centralization affect other components to make change more difficult, even after actors learn about better alternatives.

This chapter inquires into how a particular politics of spaceflight, one that privileges market mechanisms and business interests, may become potentially locked in with the ongoing privatization of space development. How have these politics shaped the outcome of major spaceflight missions such as the Asteroid Redirect Mission (ARM)? What is the potential that these politics will continue to shape the future development of celestial bodies? How exactly has this political arrangement been locked in vis-à-vis the sociotechnical system of spaceflight?

The aim of this chapter is to characterize the myriad manifestations of lock-in coinciding with the privatization of space flight. Unlike the previous chapter, these examples are not organized chronologically. Rather, they are analyzed in order to investigate the ways in which lock-in has already begun in certain aspects of spaceflight, how particular technologies potentially increases future lock-in, and the consequences of further locking in the current trajectory of private spaceflight. By first addressing the Asteroid Redirect Mission (ARM) specifically, then generalizing to the cases of asteroid mining and the private launch industry, this chapter seeks to both characterize lock-in through case studies and to show specifically where it is increasing obduracy within spaceflight.

4.2 Characterizing Lock-in

Lock-in is an outcome from which it is difficult to exit. Like a ball rolling precariously upon a peak, perturbations in any direction will cause the ball to roll downward until it reaches a saddle, at which point force must be applied to move the ball elsewhere (Arthur 1994b, 115). For example, although some partisans may want to utilize alternative forms of nuclear energy, utilities are likely stuck with light water reactors for the foreseeable future (Joseph G. Morone and Woodhouse 1989). Selection of technologies through accumulation can lead to outcomes being locked in: without the application of force, people are stuck with that outcome, even though it may be obviously inferior when subjected to analysis. Such is technological lock-in that it becomes difficult to select alternative technologies once one particular outcome has become established. All other courses require often tremendous effort to follow.

To better understand technological lock-in we might take the simple example of the red delicious apple. The red delicious is the most produced, and yet the least popular, apple in the United States. In 1893 when it was first submitted for tasting at a contest in Missouri, it was considered delicious (Yager 2014), especially compared to the Ben Davis, the most widely cultivated apple at the time which tasted bad but was tough enough to survive shipping given the limited transportation technology of the time. One day, in 1923, a chance mutation caused the apple to redden earlier and more uniformly (Yager 2014). The good looking fruit from this mutation took over as the dominant selection of red delicious. It was a good mutation for industrial agriculture, which continued to select for such traits: they turned red before they were fully ripe, they stored for longer, they had thick skins, and the deep red hid bruises. Beneath the lipstick shine, however, the flesh was sickly sweet and pulpy. The few dominant large orchards had locked themselves into the red delicious. The apple remained popular up through the 1990s, despite technological advancement that should have enabled adoption of other more delicious varieties. The U.S. was already producing varieties like the Gala and Fuji, but mostly for overseas export, while the tough, good looking skin of the red delicious provided fewer and fewer benefits with better transportation networks and refrigeration. Despite the red delicious being rendered obsolete by transportation advancements and better tasting apples, it remained locked in for nearly 100 years as the dominant apple in America.

Lock-in can extend beyond the selection of particular technological artifacts to the selection of social and technical relations. This is because lock-in does not only apply to artifacts. *People* can also be locked in to or out of decision making and agenda setting processes. The outcomes of sociotechnical accumulation are not limited to the selection of some artifacts over others, but also include the selection of some partisans over others. Because artifacts have politics, and technology can thus act like legislation (Winner 1977, 1980), the lock-in of particular technological systems also means the lock-in of political winners and losers based on that technology. This can be relatively innocuous, as when one company gains a greater market share over another. However, lock-in can also empower particular social groups to disproportionately set the agenda for future development or to have disproportionate decision making authority over other interested partisans. The consequence of such a lock-in of partisan authority and influence is that fewer standpoints guide future development. The domination of some partisan groups over others as the result of lock-in thus contributes to growing obduracy beyond just the lock-in of any given artifact.

When one technology or social group becomes locked in, this implies in return that other technologies and social groups must be locked out. Although some might consider it obvious, there are important implications worth explicit discussion. Lock-out necessarily narrows potential options. First, lock-out could foreclose superior technological pathways. For instance, the high rate of initial improvement for the light water nuclear reactor all but ensured the dominant use of this technology in nuclear energy production even though alternatives are potentially more desirable from a safety standpoint (Joseph G. Morone and Woodhouse 1989). “Early superiority is no guarantee of long-term fitness” (Arthur 1994b, 10, 116). Lock-in can be costly, potentially creating a choice between continuing to pursue the inferior option and using capital resources (financial capital, but also labor, social, and political capital) to change pathways. There is, of course, no guarantee that the resources expended to switch to the superior option will be worth the gains, and so such a decision is likely better avoided.

Alternatively, economist W. Brian Arthur (1994) notes that lock-out may be undone through unintentional coordination, where users are sure that others will switch away from the locked in technology and so themselves switch, thus reducing the costs of doing so (Arthur 1994b, 117). If he is correct, then reducing the barriers to decentralized coordination may be a superior strategy to more expert oriented central planning. Second, locking out social groups reduces the diversity of viewpoints available to help set agendas and make decisions, such as when the predominance of "true believers" within the Atomic Energy Commission excluded questions of safety or social good from primary consideration (Joseph G. Morone and Woodhouse 1989). Political theorists argue that such deficits in diversity reduce the robustness and intelligence of democratic decision making (Lindblom 1965; Dahl 1982). The greater diversity of social groups which have substantial input, the more likely alternatives are going to be more thoroughly considered.

4.3 Lock-in of Business Interests in the Asteroid Redirect Mission

ARM is notable for the inclusion of mechanisms for direct citizen participation, but also for its political failure and critiques about the influence of policy insiders. As part of the mission development process, NASA held a participatory technology assessment, which entailed creating a forum in which citizens discuss their perceptions, concerns, and values, in conjunction with the Expert and Citizen Assessment of Science and Technology (ECAST) Network (Tomblin et al. 2015). The ECAST study involved a total of 200 citizens in two deliberations, and was designed to give NASA officials a better understanding of public values associated with the ARM mission (Tomblin et al. 2015, 4–5). The inclusion of this decision-making mechanism draws on the understanding from STS (Durant 1999; Irwin and Wynne 2004; Wynne 2006; S. Brown 2009) that engagement with citizens requires more than just filling a perceived deficit of understanding, instead requiring a more active multi-directional dialogue that allows citizens to have genuine input on scientific decisions.

Despite this laudable and internally well executed ECAST study, ARM failed to gain political traction with the representatives of the people that ARM was supposed to have engaged. In addition, the participatory assessment did not protect ARM from critique on the grounds that it was unduly influenced by political insiders (Cowing 2015). This result seems, at least intuitively, unexpected. Though gaining congressional and other political support were not explicit goals of the ECAST study, still, it is surprising that such secondary benefits did not occur. One might assume that a mission developed with input from average citizens should be more amenable to elected representatives looking to get votes from participating constituents. One might also assume that appeals to participatory democratic mechanisms might have protected the ARM mission from the charge of pandering to political insiders. After all, when diverse groups are involved in making a decision, any one group should have less influence over the outcome. Yet ARM fell victim in both cases. As such, it is productive to ask, “why?” Why wasn’t ARM politically successful? What interests was ARM originally designed to meet? How did these interests become narrowed?

ARM has three major stages. First, asteroid identification: detecting, characterizing, and selecting near Earth asteroids (NEAs) for the mission. Second, asteroid redirect: redirecting the asteroid into lunar orbit. Third, human exploration: sending crewed spacecraft to explore and return samples from the asteroid (Gerstenmaier et al. 2013). The ostensible goals of ARM are manifold. ARM does not target asteroids as a destination in and of themselves, as is usually the case, but rather uses the mission to build various space related capabilities. Each stage of the mission is supposed to further the goals of the mission itself, but also accomplish external goals. The identification stage does provide the necessary information to accomplish the rest of the mission, but it may also vastly increase the awareness of potentially threatening asteroids and provide more data for selection of asteroids for potential resource extraction. Redirecting asteroids could provide a safe and controlled test case for asteroid deflection in case a hazardous collision is identified, as well as a technical test for ways of extracting and relocating an asteroid's resources. Crewed missions provide an opportunity to gradually scale up capabilities that would enable deep space missions, for example to Mars, without having to necessarily dedicate the resources to developing a deep space program that might end up crowding-out other spaceflight goals (Gerstenmaier et al. 2013).

Taking the proposal at face value, it would seem to be doing things intelligently. The mission's design appears to maintain flexibility and address public concerns. How did the mission end up becoming narrowed to reflect the interests of small groups of insiders, losing the broader goals assigned to it from the outset?

The basis for ARM comes from the Keck proposal for asteroid retrieval (Brophy et al. 2012). Because this proposal articulates a position coincident with corporate asteroid mining interests, these interests also become foundational to the development of ARM. Several of the authors have direct connections to asteroid mining interests. Chris Lewicki is the President and CEO of Planetary Resources, a company for which another author, Tom Jones, serves as an advisor. J.S. Lewis is the Chief Scientist for Deep Space Industries (DSI) along with another author, Marco Tantardini, who is an advisor for the company. Only one of these authors had their affiliation identified in the document. Given these affiliations, it makes sense that the proposal would share substantial aspects of the position of these companies. This is not to say that the authors were disingenuous or crookedly self serving in the authorship of the Keck proposal. But such connections can influence researchers' ideas and, at the very least, these connections exist because of ideological similarities or similarities of goals and agendas. Indeed, the priority of asteroid development is clearly reflected in the writing of the Keck proposal. The "key example" of the usefulness of the mission from this report is to "jump-start an entire *in situ* resource utilization (ISRU) industry" (Brophy et al. 2012, 6). The report reflects the language used in the plans of Planetary Resources and DSI as well: "Water or other material extracted from a returned, volatile-rich NEA could provide affordable shielding against galactic cosmic rays. The extracted water could also be used for propellant to transport the shielded habitat" (Brophy et al. 2012, 6).

The Keck proposal does identify other rationales for an ARM type mission. But, as ARM began to solidify as a mission, the specifics of its operation precluded substantial gains towards these non-commercial objectives. The Keck proposal presents two other central rationales for an asteroid mission like ARM. These are "Synergy with planetary defense" and "expansion of international cooperation in space" (Brophy et al. 2012, 10–11). NASA managers further identified benefits to scientific study by returning asteroid samples to Earth and to further human exploration through use of ARM as a stepping stone to longer duration missions (Gerstenmaier et al. 2013). What happened to planetary defense, international cooperation, scientific study, and space exploration development as decision makers proceeded with ARM?

In theory identifying asteroids for potential exploitation could also help identify potentially threatening asteroids earlier, and the same spacecraft components and techniques for bringing an asteroid into orbit could also be used for deflecting an asteroid away from an Earth bound trajectory. However, changes in ARM as the mission progressed further, precluded the additional goal of planetary defense. First, asteroid resource studies seem to indicate that the largest most threatening NEAs are Silicaceous (S-type) asteroids, mostly consisting of rock and iron. Without valuable elements or hydrate minerals (minerals with water), these asteroids are not good targets for mining companies. Therefore asteroids which are suitable for mining are largely different classes of asteroids than those that pose the most substantial threat to humans (Lewis 2015, 76–78). Hence, surveys of minable NEAs would contribute little to the improved understanding of asteroids that threaten Earth.

The original design of ARM would have been a useful test of asteroid deflection techniques. The mission called for launching a robotic spacecraft to a small, five to seven meter diameter and 500-1000 metric ton, asteroid. The spacecraft would then use gravity to capture the asteroid and tow into lunar orbit. Once there, astronauts would rendezvous with the asteroid and return samples back to Earth (M. S. Smith 2013). This became known as "option A." In July 2014, the NASA Advisory Council (NAC), expressed concern about the possibility of cost growth forcing NASA to make unexpected compromises in the program's content. The NAC recommended that NASA conduct an independent cost and technical assessment of the mission (Squyres 2015). NASA had to choose between the above option A, or an option B, which was to target a larger asteroid, but use a robotic arm to lift a smaller boulder, up to four meters in diameter, and fly that to lunar orbit (Gates et al. 2015). In March of 2015, NASA administrators selected option B. Selecting option B increases the cost of the mission by $100 million, despite the ostensible purpose of the study to help prevent cost growth (M. S. Smith 2015b). In addition, by selecting option B, NASA fundamentally altered the focus from the whole asteroid, to a small chunk of one. Moving a single boulder from an asteroid will not tell scientists anything about how effective technologies might be at deflecting hazardous asteroids. Although NASA plans on utilizing the time the craft will orbit the asteroid looking for the right boulder to also examine how the craft's gravity affects the asteroid (Mahoney 2016b), it is unclear if such a technique would be scalable. Therefore, not only is planetary defense a secondary consideration, but changes in the mission have sacrificed ARM's efficacy at this potential goal, and required an increase in budget to do so.

It is possible that some configurations of asteroid missions might enhance international cooperation, but the particular arrangement of ARM may not meet this criterion from the Keck report. Other nations have also recently invested in missions to study NEAs. The Japanese Aerospace Exploration Agency (JAXA) has two missions dedicated to studying asteroids, Hayabusa I and II ("Asteroid Explorer 'HAYABUSA' (MUSES-C)" 2016; "Asteroid Explorer 'Hayabusa2'" 2016). The European Space Agency (ESA) sent the Rosetta spacecraft and the Philae lander to study a comet as it enters the inner solar system ("Rosetta | Rendezvous with a Comet" n.d.). One might expect some sort of synergy between an ARM mission and the technoscientific communities in Japan and Europe that have emerged around their respective missions. On the other hand, this means that these nations have already invested substantial resources into their own studies, and the incentive to invest in a more expensive human spaceflight mission with the U.S. is not high. Generally, human spaceflight to asteroids is too expensive and risky to attract international partners (Pace 2016). Furthermore, asteroid mining is not on the national agendas of most of these nations[6], so there is a conflict between any mission that focuses on asteroid mining, and the agendas of potential partner nations.

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[6] Luxemburg is a notable exception.

These changes have decreased the applicability of ARM to scientific interests as well. The primary scientific benefit of ARM is returning asteroid samples, which offers very little gain in comparison to the cost. NASA already has a robotic asteroid sample return mission, OSIRIS-REx, which costs substantially less than the estimated $1.25 billion for the robotic portion of ARM, plus an as yet unknown cost for the crewed mission, which is required for any sample return (Mahoney 2016b). Also, the many already discussed asteroid missions by ESA and JAXA reduces the relative value of the expensive ARM mission compared to spending far less money on more scientifically targeted missions or providing funding for scientists to analyze the already existing data. Scientific interests are clearly secondary, if not tertiary, to ARM.

NASA's decision to increase the cost of the mission while sacrificing mission goals seems to be even more strategically strange given cost concerns voiced by members of Congress (M. S. Smith 2015c). In 2016, the U.S. House of Representatives sent a strong message of disapproval to NASA by proposing to deny direct funding to ARM in the NASA 2017 Appropriations Bill (M. S. Smith 2016). Given a choice between a more or a less expensive option for the same mission, Congress seems to prefer the less expensive option, especially for a mission which many members are lukewarm on already. NASA's reasoning is that the cost increase for option B enables the demonstration of more useful technologies. Associate Administrator Robert Lightfoot argued that the spacecraft bus in particular has "tremendous applicability" to industry (M. S. Smith 2015b). Already, both Planetary Resources and DSI were selected to have secondary payloads on ARM (Mahoney 2016a). Such insensitivity to the public concerns voiced by members of Congress underscores the mission's privileging of commercial interests.

The ostensible primary purpose for ARM is as a stepping stone for an eventual mission to Mars (Bolden 2015). However, this too has been undermined by mission choices that serve corporate asteroid mining interests. There are two mechanics of the mission that contribute to this goal. The first is the use of experimental high-power solar electric propulsion (SEP) (Bolden 2015). A long duration trip to Mars, or anywhere else in the solar system, will certainly benefit from improvements over current chemical propulsion. But such technology could be tested without the entire first step of the mission: robotically bringing a boulder from an asteroid back into lunar orbit. An orbit around the Moon or a trip to a Lagrange point would be sufficient. The second is mid-duration cis-lunar human spaceflight. Spending several weeks outside of orbit, but still within the terrestrial gravity well, is important for incrementally building the experience necessary to eventually send humans to another planet (Bolden 2015). But, again, dragging a part of an asteroid to the Moon to be an artificial destination seems rather shoehorned in if the purpose of ARM is to prepare for a trip to Mars. Those design aspects of the mission that were cut or strengthened emphasized the central purpose of the mission: to meet the needs of space resource developers.

Absent congressional support, what would motivate NASA to pursue a human mission to an asteroid, whittling away mission objectives that conflict with industry objectives? One argument for why NASA has made many of these decisions about ARM despite congressional opposition is that they are compelled by the Presidential directive to send astronauts to an asteroid by 2025 (M. S. Smith 2015a). It does not appear that NASA will be ready for a multi-month trip to an asteroid in its native orbit by this date. So NASA brings the asteroid to the astronauts. But an asteroid destination was clearly an afterthought for an administration whose goal was primarily to promote private spaceflight. President Obama’s administration did not announce a new policy, but rather included the cancellation of Constellation and the new commercial crew program in the 2011 NASA budget proposal (“National Aeronautics and Space Administration

Planetary Science Fiscal Year 2010 Budget Estimates" 2009). It wasn't until months later, after strong pushback, that Obama was forced to deliver a speech at Kennedy Space Center that included the asteroid directive (Obama 2010). The Obama administration was less interested in an asteroid mission than other aspects of their space policy, so there is little political pressure on NASA from the federal government to give such emphasis to this one aspect of the President's directive.

In the absence of such pressure from Congress or the Administration, I propose that business interests have become locked in to NASA's decision making process, such that it routinely drives NASA decision making. I do not mean by this that NASA is in the pockets of industry, but rather that NASA administrators have become so accustomed to responding to commercial interests that they do so habitually. Previous chapters have already shown how market ideas and the interests of private industry have accumulated within the governance of spaceflight. Given how clearly supportive ARM is of commercial interests, I suggest that political lock-in is at least capable of explaining why NASA continues to push for such an unpopular, politically unsuccessful mission.

Yet how did commercial interests get locked-in when public participation was explicitly sought in devising ARM? While these assessments of ARM were conducted by the ECAST Network, utilizing the best available expertise for its implementation, there is evidence to indicate that its impact on actual decision-making was limited. First, the timing of the assessment was too late to have a major impact. The report from the assessment wasn't published until *after* the final ARM design was approved. The assessment itself was so late in the process that much was already decided, and deliberation was systematically limited to acceptance or rejection of the mission, with little flexibility in the mission design remaining by this point. So the decision to support the mission had little meaning in the end. Second, the results of the assessment likely had little impact on proximate decision makers. While the assessment itself was given a great deal of support from NASA, those involved were not high in the NASA bureaucracy, and there were no real incentives for those high level decision makers to pay heed to the assessment, nor any evidence indicating that they did. All of the attempts at public inclusion, while in other ways genuine, had little success in penetrating the decision-making process. So, in the end, corporate and technical agendas became locked in to ARM, while public considerations were locked out.

Despite this, the ECAST study does provide a basis for minimizing lock-in of any one interest group. However, the decisions that were eventually made about the ARM demonstrate the observation of Hagendijk and Irwin (2006) that "bureaucratic structures tend to subsume deliberative exercises within conventional process, and return quickly to 'business as usual'" (182). How might future attempts at public deliberation be more effectively integrated into decision-making while avoiding the cooption warned of by Hagendijk and Irwin? The application of some of the tenants of ITE might be positive first steps.

First, deliberative exercises should be conducted early enough in the process, while the agenda for the mission is still being set and the technology is still malleable (Woodhouse 1988; Joseph G. Morone and Woodhouse 1989; Woodhouse 2004). The development of civilian nuclear power was also marred by ignoring this rule, when debate over developmental direction did not occur until after the investment of hundreds of billions of dollars towards large reactors that could potentially experience catastrophic meltdowns (Joseph G. Morone and Woodhouse 1989). Second, the outcome of the deliberative exercise should have some level of binding decision-making authority. The impact of such exercises on lock-in are sure to be minimal if decision makers are free to ignore them at their discretion (Woodhouse 2013). Elites are not inclined to voluntarily serve interests that may be opposed to their own, so this change will likely require some sort of legal binding to force them to do so (Woodhouse 2004). Had the ECAST study been conducted in conjunction with the Keck proposal and been equally authoritative in determining the direction of the ARM, industry interests might not have come out on top at so many decision-making junctures.

Adding a greater variety and number of mechanisms that engage varying public groups would also increase the number of interests represented in the decision-making process and thereby reduce obduracy. For example, when posed with the decision between option A, moving a small asteroid into lunar orbit, or option B, relocating a small boulder from a larger asteroid, NASA might have allowed public comment. Such a strategy has been used to great effect in Japanese space policy. The Japanese Public Comment System, initiated in 1999 to increase public participation and governmental responsiveness, mandates some degree of integration into policy (NIRA 2000). In 2009, the Japanese government proposed the Basic Plan for Space policy, which was intended to increase Japan's ability to use space for military purposes. However, strong pushback in over 1500 comments led to much more subdued changes (Aoki 2009). Public comment on the ARM may not have changed the decision, but the inclusion of a greater diversity of interests would have provided increased resources and authority to those positions that were otherwise excluded from decision-making and therefore decrease lock-in.

The *agenda* directing the ARM was set by business interests such that the mission's most substantial accomplishment is likely to be foundational R&D for the creation of an asteroid mining industry rather than the increase in spaceflight flexibility and public participation that many NASA policymakers likely intended. ARM could thus be characterized as a failure because the lock-in of particular business interests decreased the flexibility of the mission by focusing the technical mechanics of the mission to accomplish those goals most relevant to them at the expense of other mission goals, thus reducing the mission's contribution to a diversity of available future pathways.

4.4 Inflexibility of Asteroid Mining

Agenda setting is one of the mechanisms through which the interests of certain groups gets locked in. Indeed, contributing to the lock-in of the space shuttle were long lead times for development, a small fleet of shuttles, high capital intensity, and high infrastructure dependence. Because the shuttle took so long to develop, the design was highly inflexible by the time it was tested in actual flight. With so few shuttles, any setback with one shuttle caused a chain reaction of problems. Because so much of the expense was in development, those costs could only be recouped by routine flights, which never materialized. Finally, high infrastructure dependence prevented accurate reflection on the cause of errors and discouraged error correction (Collingridge 1990, 1992). Are there similar examples in contemporary private spaceflight where commercial interests might be locked in via infrastructural commitments? Asteroid mining might be one such example. What activities could asteroid mining support? How would these activities depend on asteroid mining?

The ostensible rationale for asteroid development is "synergy with near-term human exploration" and "exploitation of asteroid resources" (Brophy et al. 2012, 9–12). In general, the resources from asteroid development can be broken down into two categories: space exploration resources and terrestrial resources. The first are resources that are useful for furthering continued and more distant space exploration because of their importance to those activities and their difficulty to get into space. The second are resources that are important for uses on Earth but are not abundant there. The argument for terrestrial resources is that there are several elements which are rare on Earth, but relatively abundant on asteroids, and are extremely useful. These elements are platinum group elements, rare Earth elements, and alkali elements (ex. Lithium).

While the terrestrial argument might appear well-founded, the underlying economics is less than certain. The most valuable of these elements is Platinum which at the time of writing is valued at approximately $1 thousand per ounce, or $16 thousand per pound. In order to be profitable, the price of the platinum that could be sold must exceed the costs of its extraction and transportation back to Earth. One the one hand, the estimated return of platinum from asteroid mining is 50% of current global output (Andrews et al. 2015). If one assumes the platinum is being sold at current market rates, it would be very profitable to mine from asteroids. However, a supply increase of 50% of the current global output would almost certainly lower prices. Things look little better on the demand side. 50% of demand for platinum comes from its use in catalytic converters (Royal Society of Chemistry 2016). The other 50% of demand is for platinum as a catalyst for production of nitric acid, silicone, and benzene as well as for fuel cells, electronics such as computer hard disks, other manufacturing such as LCD screens and wind turbines, a component of chemotherapy drugs, and finally jewelry. As electric vehicles become more common and market shares for internal combustion engines, and therefore catalytic converters, go down, the demand for platinum will also go down. While the price of platinum given asteroid mining is unpredictable, a 50% increase in global supply coupled with a reduction in the largest source of demand for platinum will almost certainly drop the price by a large margin. Given that platinum is the most profitable element to mine from asteroids, the profitability of mining asteroids for terrestrial use seems questionable at best.

However, mining asteroids for space exploration resources is another story. Water extracted from hydrate minerals is the primary resource asteroid mining companies plan to extract for space exploration. Astronauts, of course, need water to drink. It can be refined into oxygen for breathing and hydrogen can be processed into rocket fuel. Hydrogen and oxygen are both relatively abundant elements in the solar system, and so many rocky asteroids are composed of hydrate minerals (Lewis 2015, 78) which can be processed into water.

Water is relatively abundant on Earth, so conventional supply and demand models would predict asteroid water to be completely unprofitable. But the profitability of asteroid mining for water has been understood in relation to the cost of moving water into low Earth orbit (LEO). Rather than demand, space resource economists utilize the concept of "demandite," or "the sum of the elemental abundances of consumables that must be mined to support civilization" (Criswell 1977; Lewis 2015, 98–99). In other words, demand is determined by the necessities of the mission goals. Customers purchase goods for spaceflight based on what the mission requires for completion, and at a price determined by the cost of getting it into space. Prices don't fluctuate solely from supply and demand. Water and fuel are both essential to spaceflight and, when using the space shuttle, cost $10 thousand per pound to LEO. This puts water to LEO at just under the cost of platinum on Earth. The asymptotic lowest possible value given current technology is $1 thousand per pound to LEO (Taylor et al. 2008). This assumes perfect reusability, however, which means that it is only approximately attainable if a launch vehicle launches so frequently and the refurbishment costs are so low that nearly the entire price to orbit comes from initial development costs.

Actual prices for asteroid water will be somewhere in between the current value and the low estimate. Elon Musk estimates that the Falcon 9 can *potentially* reach as low as $1200/lb to

LEO, actual performance to date places that price closer to $2500/lb to LEO (Chaikin 2012). This may also increase if government subsidies (for example federally covered launch insurance) are reduced. The reduction Musk has achieved is still one quarter of the cost to LEO of the shuttle. Asteroid mining itself will be very expensive, including finding appropriate asteroids, developing the necessary technologies, launching the equipment and supplies, extracting, enriching, and processing the asteroid's resources, and transporting the product to sites of demand (Lewis 2015, 98). Mining water to support other spaceflight activities seem more likely to be profitable than mining minerals for use on Earth, but if spaceflight is limited to only orbital activity profits might not be enough to overcome the large initial investment necessary.

But, there is a reason why the Keck report indicates first that asteroid development supports "synergy with near-term human *exploration*." Because launch costs go exponentially up for the distance traveled, long duration deep space missions are a potentially good market for asteroid resources. Going to orbit and going to Mars are two very different undertakings. The further a space craft needs to travel, the more fuel and supplies it needs. These things make the craft heavier, which requires even more fuel, which increases the weight, and requires more fuel, and so on. This is why the cost of launch vehicles increases so drastically with the size of the payload or the distance to the destination. For travel to Mars, we can expect substantial increases in price. Several uncrewed missions have already been launched to Mars aboard Atlas V launch vehicles which provides a useful cost estimate. Looking at the Mars Reconnaissance Orbiter (MRO), the Atlas V cost $90 million to launch and the payload was 4018 pounds (Beasley et al. 2005). The Mars Science Lab (MSL) also launched aboard an Atlas V, cost $215 million to launch, and weighed in at 8463 pounds ("National Aeronautics and Space Administration Planetary Science Fiscal Year 2010 Budget Estimates" 2009, SCI-139). Thus, the cost per pound to Mars was $22.4 thousand for MRO and $25.5 thousand for MSL. The cost would likely go up exponentially for human missions, and even if engineers do increase launch efficiency for deep space missions, the price of water for such missions seem much more amenable to the bottom lines of asteroid resource companies.

SpaceX, however, quotes the cost of taking 30,000 pounds of payload to Mars on their Falcon Heavy launch vehicle at $90 million, which comes out to $3000 per pound to Mars (Space Exploration Technologies 2012b). This is likely an overly rosy prediction. If this prediction were based on the expected technical efficiency of the Falcon Heavy alone, SpaceX would have to achieve a manifold increase in efficiency over their current Falcon 9 launch vehicle. This seems unlikely, as the Falcon Heavy uses essentially the same technologies but on a larger scale. Their estimate seems quite optimistic. At the time of this estimate, the Falcon Heavy did not yet exist, so a more logical explanation is that SpaceX is already assuming the existence of a dedicated asteroid mining or other infrastructure to keep payloads (and hence costs) down.

The implication of this analysis is that asteroid mining may only be commercially viable in support of deep space exploration. While there is nothing problematic about deep space exploration in and of itself, this does run afoul of Collingridge's criteria of dedicated infrastructure for inflexibility (Collingridge 1992). For instance, the need to develop expensive dedicated infrastructure for the space shuttle prevented analysts from knowing the price per pound of shuttle payloads until the shuttle was finished and operational. By then, the cost of correcting errors was exorbitant, and the consequences of those errors were severe and far reaching. The optimistic predictions about the cost of the space shuttle were proven false, there was little to be done about it afterwards, and even after the fact it is impossible to tell if the inflated costs of development were due to sub-optimal design or the expense of the dedicated infrastructure itself. In the case of asteroids mining, the situation is potentially similar. Deep space exploration will likely rely upon the resources from asteroid development, and asteroid development remains viable only with continued deep space exploration. The dependence of an entire resource extraction industry on deep space exploration would make policy makers reticent to stop or slow down that exploration even if such slowdowns were necessary to prevent or reduce substantial harms. Thus, as things stand, asteroid mining would be a dedicated infrastructure, which would lock spaceflight into a very particular trajectory, and force decision makers to choose between staying the course and accepting those harms, or causing potentially great economic harm in order to pursue a different pathway.

It may very well be that there are no feasible contemporary scenarios in which asteroid mining does not produce a dedicated infrastructure. It may be that asteroid mining and deep space exploration are completely interdependent. Given this possibility, the option to reject asteroid mining must be available. One advantage of market mechanisms is that rejection is always available given market failure. However, that does not mean that the conditions for market failure coincide with conditions for obduracy. Asteroid mining may succeed in the market, yet still comprise a dedicated infrastructure. How many possible uses for asteroid resources are required for at least one company to turn a profit? Will supporting deep space exploration be enough? Or will the endeavor fail without additional benefits? Given that this is unknown, and unpredictable, non-market mechanisms should be available to reject asteroid mining until it is clearer that market mechanisms are sufficient.

In their study of democratic expertise, Woodhouse and Nieusma (2001) identify several strategies which might be useful for the case of private space development as well. Of particular importance is the broad recognition of shortcomings in expert analysis, such as inherent partisanship and uncertainty. In the case of asteroid mining, policies are likely to produce less obduracy if most parties recognize that there are some conditions in which asteroid mining becomes unacceptable. This contrasts with the prevailing attitude among spaceflight proponents that any space development is always better than none.

Starting with the recognition that even the staunchest supporters should have some conditions that would cause them to reject any proposal, it is not too large of a leap to put in place some system of monitoring to watch for those conditions. Morone and Woodhouse (1986) describe a system of multi-partisan monitoring. Such a system is more likely to be reliable: the various partisan groups are likely to keep one another in check, preventing dishonesty and looking for errors that one partisan group alone might ignore or simply miss. It would also be quick to catch errors because each partisan group is incentivized to find errors with competing proposals or policies. For example, the relatively balanced positions of employers, labor unions, scientists, and state agencies has enabled decent progress in some occupational health endeavors (Woodhouse 1995, 401–3). In the case of asteroid mining, a monitoring agency that supports internal monitoring by industry experts as well as external monitoring by competing industries, relevant labor unions, and even detractors of spaceflight would be more likely to identify potential lock-in than current forms of monitoring which are mostly limited to examining human safety and contract compliance.

Finally, even if it becomes clear to most actors that aspects of space development such as asteroid mining are going awry, inflexibility and lock-in may still prevent action to alleviate errors. Some incentives for error correction may help to counteract this effect (Joseph G. Morone and Woodhouse 1986). As has already been demonstrated, should asteroid mining proceed as a dedicated infrastructure, it will include strong incentives to stay the course, even in the face of egregious errors that need correcting. In general, buyers and sellers in a market have little incentive to account for 3rd parties which therefore means that the private sector rarely accounts for public considerations (Lindblom 2001). To provide a more specific example, in New Orleans, housing construction is delegated to private developers, as is the case in most of the U.S. As profit seeking companies, they were incentivized to use standard slab construction for houses and to ignore existing local construction techniques specifically designed to mitigate against flood damage (Woodhouse 2013, 66–67). As a counter example showing the potential effectiveness of incentives for error correction, the excise tax on gasoline sales reduced the barrier to road maintenance that would have otherwise been caused by expense (Woodhouse 2013, 71). Thus, building counter-incentives into policy could go a long way to improving learning and thus decreasing lock-in.

One way of supporting these requirements might be to have asteroid companies supply the burden of proof. As it stands, the default position is that asteroid mining endeavors should be free to pursue their objectives (with some help from the government) either indefinitely or until the market will no longer bear their activities. What if asteroid mining companies first had to sufficiently prove, in the minds of lawmakers, that the market would require sufficient diversity before congress would pass promotional legislation? Such a system would likely protect against lock-in.

Beyond the lock-in that has been demonstrated by the political failure of ARM, commercial asteroid mining in general meets some of the criteria for inflexibility. If commercial asteroid mining is an inflexible technological system, then it seems all the more likely that it will contribute to the lock-in of a potentially regrettable path of technological development.

4.5 Lock-in Through Inflexibility

Spaceflight has historically been prone to inflexible technologies. The space shuttle met all four of Collingridge's criteria for inflexibility. With development lasting a decade, the lead times were certainly very long. Most of the expenditures on the space shuttle were in development rather than operation, and although no public record indicates the total cost of development, it was certainly exceptionally large, and irrecoverable. With only four launch vehicles in the fleet at any time, the unit size was large as well (Collingridge 1992, 29). In addition, the shuttle had to replace the work of 12 existing launch vehicles to approach a low price per launch. The unique capacity of the shuttle also meant that important payloads were designed explicitly to be launched on it. So some payloads required the shuttle which had to be balanced with the multitude of other payloads the shuttle needed to launch to keep prices down. The size of the shuttle meant that multiple payloads were launched per mission. This led to scheduling confusion that was dealt with via increasingly centralized decision-making and which muddied NASA's ability to identify and rectify errors (Collingridge 1990, 188–90).

Inflexibility for the space shuttle resulted in a reduced ability to learn via trial and error. The consequences of which were a program plagued by errors with severe and costly consequences. Furthermore, in the case of asteroid mining, we see that dedicated infrastructure, an important component of inflexibility, also potentially contributes to lock-in. Are there other situations of inflexibility within private spaceflight? What are the potential consequences of technological inflexibility for privatized spaceflight? To what extent has privatization generated centralization and dependence?

The first indication of inflexibility is that the seeming plethora of commercial activity belies the limited diversity of launch options. The Commercial Orbital Transportation Services program (COTS) was designed to seed the development of private launch vehicles that could supply the ISS. SpaceX and Rocketplane Kistler (RpK) won the first round of funding, but RpK was replaced by Orbital Science Corporation[7] after they failed to meet the requirement for raising private capital (Alan J. Lindenmoyer 2012; Bretton Alexander 2013). Both companies won contracts for the Commercial Resupply Services (CRS) program to use the launch vehicles and supply capsules each company developed through the COTS program to resupply the ISS (Gerstenmaier 2013). The still ongoing Commercial Crew Development (CCDev) program consists of several stages and uses a funding model similar to that of COTS where participants are granted startup capital after meeting certain self-ascribed milestones. As of writing, NASA has funded the third stage, called Commercial Crew integrated Capability (CCiCap), which calls for end-to-end designs for crew transportation to the ISS. Three companies were selected in this third round of SAAs to develop spacecraft capable of carrying crews to LEO: SpaceX, Sierra Nevada, and Boeing (Gerstenmaier 2012b; Thomas and Perrotto 2012). In addition, Blue Origin had been selected for the first two rounds of funding, but not the third, and continued development without additional NASA funding. NASA has expedited contracts for commercial crew services, Commercial Crew Transporation Capability (CCTCap), and has awarded second phase contracts, Certification Products Contracts (CPC) to SpaceX and Boeing. Sierra Nevada was not selected despite challenging the decision with the Government Accountability Office (GAO) (Bolden 2014; Scordo 2014; Martin 2015). So the list of participating companies seems rather large. SpaceX, Orbital ATK, Sierra Nevada, Boeing, and Blue Origin have all gotten NASA funding for commercial spaceflight services.

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[7] Now Orbital ATK after a merger with Alliant Techsystems, known as ATK.

Do all of these competing companies result in an equally diverse set of options? SpaceX currently has one launch vehicle in operation, the Falcon 9, which launches the Dragon spacecraft. Orbital has one launch vehicle in operation, the Anteres, which launches the Cygnus spacecraft. Neither Sierra Nevada nor Boeing have their own launch vehicles. They both use the Atlas V, from United Launch Alliance (ULA). Sierra Nevada has the Dream Chaser spacecraft, and Boeing has the CST-100 spacecraft. Both SpaceX and ULA have new launchers in development, the Falcon Heavy and Vulcan respectively. Aside from Orbital Science, which is not pursuing human spaceflight, the only launch vehicles proposed for commercial crew are the Falcon 9, and the Atlas V. While the Atlas V has a very long history of successful flights, and has been used by NASA for many of their deep space robotic missions, the reliance on Russian engines for this launch vehicle has become a problem (Gruss 2014a) and it will soon be replaced by the Vulcan launch vehicle, currently under development by ULA. The current outlook for private human spaceflight is a mere two launch vehicles. If something were to happen to delay, prevent, or reduce the capabilities of ULA's Vulcan launch vehicle, then as private missions become even more far reaching, going to the Moon, asteroids, or even Mars, they will be highly dependent on a single launch vehicle owned by a single company: the falcon series launch vehicles owned by SpaceX.

What are the likely consequences of this level of dependence? While many fear that commercialization sacrifices safety compared to a public program (Pace 2016), my analysis will consider the potential consequences more broadly. Consider the space shuttle. The space shuttle had very high infrastructure dependence. In order to be flown cheaply, as a reusable launch vehicle with high development costs, it needed to be flown frequently, which in turn required the federal government to suppress alternatives. Without sufficient alternatives, the Challenger disaster had severe consequences even beyond the deaths of the astronauts. New restrictions threw the satellite industry into chaos, with little development of market alternatives to the shuttle to rely on once the shuttle was not an option. The Department of Defense had also relied on the shuttle: their reconnaissance satellites required the large payload bay of the space shuttle. So when problems with the space shuttle arose, they had no alternatives. The high costs being focused on the development rather than the operation of the shuttle meant that those costs were not recoverable if NASA desired to pursue an alternative (Collingridge 1990, 1992, 21–39).

There is little reason to expect privatization to substantially improve the situation. Whatever efficiencies resulting or not from privatization does not eliminate the effects of having to rely on only one or two launch vehicles. Such inflexibility increases the severity of consequences independent of the private or public governance of spaceflight: accidents cause large delays and can potentially eliminate some programs dependent on them.

In much the same way that reliance on asteroid mining for water makes necessary changes to space development more difficult to accomplish, having one particular dominant launch vehicle creates a situation of infrastructural dependence. If the Falcon launch vehicle is found to be insufficiently safe or otherwise inadequate, market participants will have a substantial incentive to resist change, even if those changes are beneficial for the public. In the same way that NASA “stayed the course” with shuttle (or the American Nuclear Energy industry with the light water reactor), reliance on Falcon locks in both particular technological artifacts as well as business interest and decision makers.

Dependent infrastructures, such as a dominant launch vehicle or water from asteroids, also creates a situation that is detrimental for learning. What might such a space program look like? SpaceX and Bigelow Aerospace entered into an agreement in 2014 for future launches. Bigelow

Aerospace creates inflatable space habitats. NASA has supported the opportunity this creates for low cost space habitation, exemplified through the Bigelow Expandable Activity Module (BEAM) which is now part of the ISS (Mahoney 2015). Orbital hotels are the most well known aspect of Bigelow's business model, but their habitats are also marketed as inexpensive locations for micro-gravity research, modules for deep space human spaceflight missions, habitats for extraterrestrial colonization, or stations for resource extraction operations ("About Bigelow Aerospace" 2016). To test their technology, and at the same time signal NASA's support and gain the credibility of working with NASA, Bigelow attached one of their inflatable modules to the ISS in spring of 2016. Their module was taken to the ISS by a Falcon 9 as well. Taking into account this program as well as all those already analyzed in this chapter gives some idea of what the imagined future of the most influential spaceflight entrepreneurs looks like, or at least an example of an inflexible and obdurate pathway for development. Planetary Science purchases or leases Bigelow modules for the establishment of asteroid mining operations which are launched on Falcons. These asteroid mining outposts are then used by SpaceX when they send their mission to Mars using Bigelow modules as the beginning of their base. These tightly coupled relationships between private firms locks out actors with alternative goals or viewpoints. Even competing companies like Boeing would be forced to redesign their capsule to work with the Falcon, incentivizing only either monopoly or collusion. Thus, even assuming they act altruistically (perhaps not likely), the ability of these firms to react to unexpected situations will be partial at best. Furthermore, such a system of dedicated infrastructures provides a disincentive to searching for and correcting errors because errors become exceedingly difficult and expensive to correct.

While such a vision has not been fully articulated, the current direction of private development seems likely to induce infrastructural dependence. The problem with this model is that the dependence on a small set of options, such as launch options, make the whole system very resistance to alterations resulting from learning, because there are automatic market punishments for systemic alterations not in their favor (Lindblom 1982; Collingridge 1992). For example, the mere worry of a two-year gap in American human spaceflight capabilities after the retirement of the shuttle was enough to push lawmakers to support funding privatization programs that were relatively unpopular in Congress. If the Falcon becomes the only, or even only one of two, human launch vehicles, trying to pursue alternative agendas to those supported by SpaceX may deny the U.S. access to space. In addition to consequences for telecommunications and national defense infrastructures in orbit, the prestige of spaceflight has diplomatic importance. If asteroid mining companies failed, the ability to supply colonies or other entrenched infrastructure may be compromised. If Bigelow goes out of business, who will repair and upkeep their habitats? These consequences are in addition to the more usual worries about job loss and the deskilling of the workforce that acts as an automatic market punishment in other industries. Forcing increased competition for these services, as may be desired, will be resisted passively (if not actively) through these market consequences due to the infrastructural dependence creating inflexibility and lock-in.

One of the major obstacles to reducing lock-in once it has occurred are these automatic market punishments. Fortunately, private launch vehicles are relatively early in development. They do not yet make up a large enough portion of the economy to frighten policy-makers into locking them in to any particular configuration. Thus, private launch companies are still amenable to alterations. The supporting funds for CCDev and the resulting contracts for sending crew to the ISS might include additional factors that must be met before NASA releases the funding.

First, although it will mean a longer wait until private companies deliver crew to the ISS, NASA should not conduct CCDev and CCTCap simultaneously. A key tenant of Intelligent Trial and Error (ITE) which preserves flexibility is gradual scale up (Woodhouse and Collingridge 1993). Since commercial crew builds off of commercial cargo as a model for this new organizational and funding strategy, any errors in cargo will be carried over to crew without an opportunity to learn of them and correct them. On the other hand, completing the commercial cargo program in full and then conducting a multi-partisan analysis of its success through several metrics would better enable improving the development of a commercial crew program. What NASA is sacrificing to expedite commercial crew is an increase in obduracy.

Second, NASA might require some forms of public engagement as a condition to funding. As discussed in the section analyzing the ARM, a variety of multi-partisan forms of public engagement can help reduce lock-in of particular interests. NASA already required COTS and CCDev partners to demonstrate their appeal to investors by successfully obtaining private capital. Adding requirements to appeal to a wider set of publics should not require much additional capital, too many new staff, or much new bureaucracy. Private companies might demonstrate public appeal through already existing methods of obtaining public comment, or through conducting studies similar to ECAST. Science and Technology Studies also has a robust scholarly literature of public engagement techniques (Delborne et al. 2011; Wynne 2011; Felt et al. 2014) from which executives might draw to demonstrate their public appeal.

NASA could also pursue multiple strategies for sending astronauts into space so that limited options from the private sector are less likely to result in lock-in. A key strategy for maintaining flexibility is conducting multiple trials simultaneously (Woodhouse and Collingridge 1993; Woodhouse and Nieusma 1997). Although funding is a limiting factor, several alternative strategies have already been identified which work reasonably well within current funding limits. First, NASA might benefit from increased coordination with international partners. While the Soyuz can also take astronauts to the ISS, if other nations were able to provide assistance sending astronauts to space that would reduce the reliance on private companies. Some space policy insiders have criticized the heavy focus on privatization as offering little incentive to international partners for cooperation (Pace 2016). NASA could also develop their own public options for sending astronauts to LEO. Although NASA is developing the Space Launch System (SLS), this is primarily designed for deep space missions, and not an economical or expeditious choice for LEO. These strategies, however, might be useful in conjunction. Several other nations have launch vehicles, and NASA has been developing the Orion crew capsule as an ostensible "backup" for the ISS for some time. While there are several barriers to adapting a NASA capsule to foreign launch vehicles, overcoming these barriers may result in a substantial reduction to lock-in and obduracy.

Inflexibility, especially in cases of high levels of infrastructural dependence, tends to increase the centralization decision-making (Collingridge 1992). It reduces the choices available such that only those inflexible technologies seem suitable, thus locking them in. On scales larger than individual artifacts, inflexibility may place particular companies, business leaders, or other proximate decision-makers in positions of power over whole industries without sufficiently balancing their authority, thus leading to more unintelligent decision-making than might be made with more actors all competing for influence. The specific scenario described in this chapter need not come to pass. The point is to illustrate how the contemporary form of privatization erects barriers to reducing lock-in, and to provide an analysis that helps to overcome those barriers without assuming that market mechanisms need to be rejected.

4.6 Lock-In Throughout Industry

Forms of governance themselves may also become locked in. The result of the desire to "stay the course" combining with the threat of automatic market punishment is that decision-making is constrained. It may be the case that giving markets new roles in governance can increase flexibility, as the case of the COTS program demonstrates. Through the use of private companies, NASA has diversified the set of ISS resupply launch vehicles and protected against failure. However, locking in market mechanisms as the dominant governing mentality will undo such benefits. This section examines the current direction of the launch industry. It investigates the extent to which market governance writ large is gaining influence, and the costs of this governing mentality to alternative considerations for directing governance. What other values compete with market values? How are market values reflected in the governance of spaceflight? How did the values expressed through space development become narrowed? How could privatization still be implemented while avoiding value lock-in?

Many traditional contractors have shifted their designs and business models to be oriented more towards competition and low pricing, primarily in response to NewSpace companies like SpaceX. ULA was the primary launch vehicle provider in the U.S. after the 2006 joint venture between Boeing and Lockheed Martin spun off their Evolved Expendable Launch Vehicles (EELV), the Atlas and Delta series, into a separate launch company. However, they have been feeling the pressure from newer launch providers, and SpaceX especially. In 2014, ULA CEO Tory Bruno unveiled the Vulcan launch vehicle at the 31st Space Symposium as the replacement for the Atlas and Delta launch vehicles. This new launch vehicle is a direct result of ULA's shift to more market oriented governance. The vehicle is designed to make ULA more competitive in the commercial launch market, which deviates substantially from their strategy of relying on national security payloads. It thus represents a shift in focus away from contracts, and towards more cost efficient market competition (Ray 2015). Though a much larger company, ULA executives feel as if they must conform to the market values expressed by newer companies like SpaceX.

Specific aspects of the design of the Vulcan indicate which influences from commercial competition have been most pronounced. On April 28, 2014 SpaceX filed a suit against the U.S. Air Force and ULA regarding a noncompetitive block buy of 36 launch vehicles for national security payloads (Braden 2014). SpaceX claimed that they did not wish to challenge the decision to award the contract to ULA, but rather to make such contracts open to *competition* (Post 2014; Shanklin 2014). But on April 30, the court issued a preliminary injunction banning ULA from purchasing the RD-180 rocket engines for the Atlas launch vehicles. The engines were manufactured by NPO Energomash, a Russian company which was believed to have ties to Deputy Prime Minister Rogozin of Russia who was sanctioned after the Russian invasion of Crimea (Braden 2014; End 2014; Gruss 2014a, 2014b). From this injunction, Senator John McCain of Arizona introduced a bill that would prohibit ULA from purchasing the RD-180 engines (McCain 2016a), which was then followed by another bill introduced by Senator Bill Nelson of Florida as a compromise to allow ULA access to up to 18 engines through 2022 in order to complete their contractual obligations to launch national security payloads (Nelson 2016; McCain 2016b). What started as a suit by SpaceX to increase the influence of market competition over Air Force launch contracts quickly escalated to include members of Congress, who are rarely involved at this level of decision-making. Several factors coalesced to put immense legal pressure on ULA executives to conform to the value of market competition.

Although the matter was eventually settled out of court, with ULA maintaining their contract and future contracts being opened for increased competition, ULA's design of the Vulcan is a clear response to this turn of events. The design of the Vulcan reflects not only the political situation with Russia, but also the impetus for competition which sparked the whole affair. Two American companies competed for contracts for the Vulcan's main engines: Blue Origin's BE-4 engines or Aerojet Rocketdyne's AR-1 engines. At the time of writing this decision has yet to be made, but will likely be made soon, and it seems likely that Blue Origin will be the winner (Foust 2016). While Rocketdyne is a long standing aerospace contractor, having developed the main engines for the space shuttle, Blue Origin is a NewSpace company founded in September of 2000 and founded by Amazon co-founder Jeff Bezos. The inclusion of Blue Origin as a serious contender for ULA's engine manufacturer also serves to demonstrate the shift towards market oriented governing mentalities. ULA is no longer designing rockets with only capabilities and heritage in mind, as demonstrated by their likely selection of a newer, but cheaper and more efficient, piece of hardware.

These shifts can also be seen in the company culture. A former ULA employee working on the Atlas launch vehicle describes intentional changes to more closely resemble SpaceX. He described an environment that favors a "lean" workforce, celebrating the creativity and ingenuity of the younger engineers. However, he also expressed the consequences for older employees, who were finding it more difficult to achieve acknowledgement for their work, and an increasingly hostile atmosphere towards families, as work expectations increased, such as through mandatory overtime (Anonymous 2015). Moreover, ULA has designed Vulcan with a new conception of reusability which they refer to as “thoughtful reusability.” This shift moves away from conceptualizing the benefits of reusability as increasing the frequency of launches to being about “the pure economics of it” (Ray 2015; Bruno 2015). The influence of companies like SpaceX has already caused an aerospace giant to change everything from design to company culture to focus more on reducing costs and increasing ULA’s competitiveness for payloads rather than focusing on achieving particular launch capabilities to serve national security interests.

The effects of this shift in governance away from the public sector and towards private companies have also spread internationally. Two other major international launch companies, Mitsubishi Heavy Industries (MHI) and Arianespace, have designed their next launch vehicle with the primary goals of cost reductions and increased commercial competition in mind. The Japanese government, especially JAXA, have long been the primary customer for MHI’s HII-A launch vehicle. The Japanese government has traditionally eschewed cheaper options in favor of the domestic option of the HII series (Perrett 2012). As a result, MHI has been primarily concerned with meeting the specific needs of these customers, such as payload dimensions, launch schedules, or a corporate structure more compatible with Japanese bureaucracy. But in May 17, 2013 the H3 launch vehicle was authorized by the Japanese government (Kallender-Umezu 2013). As a joint endeavor between MHI and JAXA, the hope is that the launch vehicle can be more competitive in the commercial market while minimizing sacrifices in compatibility with government missions and payloads, including Japan’s new emphasis on using space for military purposes (Bouchey 2015). Indeed, the H3 is about half the current cost of an HII-A (Kallender-Umezu 2013). This shift by the Japanese government and MHI away from a focus on meeting national spaceflight needs to price reductions and commercial competition is indicative of the influence already wielded by supporters of governance through markets.

Arianespace provides a similar story. In December of 2015 ESA decided to fund the development and production of a replacement for the current Ariane 5, designed to maintain Europe's share of the launch market in the face of new competition by American NewSpace firms (de Selding 2014). Arianespace once controlled 50% of the international launch market (Svitak 2014), due to their reputation for producing the world's most reliable launch vehicle. This allowed them to operate at slightly higher costs than they could have and justified European government subsidies. However, the shift in priorities to commercial competition and cost reductions has prompted Arianespace to sacrifice reliability. In 2014, aerospace companies Airbus and Safran proposed a joint venture to produce the new Ariane 6 and buy out the French government's stake in the company. However, their plan was criticized, specifically because the estimated launch prices were not competitive with SpaceX (Cabirol 2014). These two major aerospace companies were still operating in the old paradigm, attempting to leverage the reputation of the Ariane 5 by building a similar style launch vehicle as its successor when the impetus had become cost reductions. In the end, the development of the Ariane 6 included many aspects similar to that of the Vulcan: increased flexibility and an application of reusability not designed to increase launch frequency, but to decrease costs, eventually low enough to eliminate government subsidies to Arianespace (de Selding 2014). Instead the ESA would act much more like NASA, as a customer of services rather than an owner via traditional contract models.

The above examples all indicate that market governance of spaceflight has quickly spread around the globe. Alternative priorities aside from those dictated by market success or failure are increasingly seen as no longer acceptable and are weeded out before they are given adequate consideration. But privatization need not necessitate a loss in flexibility. What other approaches might maintain flexibility and reduce obduracy?

Compare the above cases with the COTS program. COTS was a program designed to develop commercial capabilities for providing crewless resupply to the ISS[8]. Upon completion of the program, NASA began the CRS program, through which they awarded two contracts, one to SpaceX and one to Orbital, both of which had developed resupply capabilities through COTS. The worst case scenario for ISS resupply is that a catastrophic accident prevents life sustaining supplies from reaching the space station and bankrupts the company in question, preventing further resupply and jeopardizing the future of the ISS. Catastrophic accidents have occurred three times, but without the extreme consequences one might expect. The first occurred on October 28, 2014 when Orbital Science's Antares rocket exploded on the launch pad for their third ISS resupply mission (Wall 2014). The second occurred between April 28 and May 7, 2015 when the Russian Progress 55 resupply mission malfunctioned at launch and fell back to Earth without reaching the station nine days later (L. David 2015). Finally, on June 28, 2015 SpaceX's Falcon launch vehicle broke apart in the air shortly after launch (Wall 2015) amounting to three critical mission failures in eight months.

Three critical failures in eight months seems likely to generate substantial negative scrutiny, threatening contracts or even the program as a whole. In addition, one might expect serious supply problems on the ISS after so many failed resupply missions. However, the astronauts on the ISS remained well supplied and the program suffered little setback. The reason is because, rather than rely on any single provider, private or public, to supply the space station with a perfect record, NASA and their international partners prepared for this possibility. The ISS has a

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[8] COTS was part of the Constellation program, a primarily public spaceflight program with two traditionally developed launch vehicles which would have been owned and operated by NASA.

total of five potential resupply vehicles: the SpaceX Falcon 9 launch vehicle with its Dragon capsule, Orbital's Anteres and Cygnus, the ESA's Automated Transfer Vehicle (ATV), the Russian Space Agency's (Roscosmos) Progress, and JAXA's HII Transfer Vehicle (HTV). Every resupply mission is also required to have a backup launcher prepared with supplies usually by a competing provider, and each supply delivery carries more supplies than necessary, so that in the event one launch fails another can be conducted in short order, no single provider has undue pressure put on them to succeed, and the astronauts have enough supplies to wait for a new resupply mission. NASA officials did not assume that market competition would result in increased safety, and so established safety and flexibility as explicit goals which balanced against the emphasis on cost reduction and competition inherent in privatization and market governance. In this way, COTS was not used to fully privatize resupply services to the ISS, but to supplement and add flexibility to existing public resupply options.

4.7 Conclusion

This chapter has analyzed the extent to which lock-in is contributing to the obduracy of contemporary private spaceflight. By analyzing several cases, this chapter explores a range of obdurate barriers erected through lock-in. First, lock-in of interests or social groups can lock-out competing interests, thus preventing reconsideration by centralizing decision-making. Such lock-in can cause problems for missions designed to account for or meet any competing interests. Second, lock-in can create infrastructural commitments that run afoul of Collingridge's concept of inflexibility (Collingridge 1980, 1992). The lock-in of infrastructural technologies prevents adjustment to the technological systems which are interdependent. Third, lock-in can limit the number of actors taking on the role of proximate decision makers in a technological system. The lock-in of a technology or social group increases the influence of those decision makers proximate to that technology or group. This generates a reliance on particular technologies or people, which hinders the identification and rectification or errors. Finally, as lock-in spreads throughout an industry, it can create disincentives to improvement. Fear of automatic market punishments, such as loss of jobs, or loss of national prestige, grow along with lock-in and can contribute to the resistance against changing to alternative technosocial configurations even if the consequences become severe.

The goals of this chapter are to better understand the potential outcomes of lock-in for private spaceflight, and analyze the extent to which lock-in already has erected barriers to alternative configurations of space development. How have industry interests shaped the outcome of major spaceflight missions? What is the potential that these policies will continue to shape the future development of celestial bodies? How exactly has the political arrangement of privatization been locked in vis-à-vis the sociotechnical system of spaceflight? This chapter has worked to answer these questions through the detailed examination of several cases of contemporary spaceflight.

By examining NASA's ARM mission, this chapter has show how industry interests have become locked in to the mission design at the expense of goals derived from other interests. The inclusion of industry interests in setting the agenda for the mission resulted in the elimination of competing mission goals whenever they conflicted. The design of the mission at the time of writing is unlikely to provide experience for planetary protection, and design changes reduced the cost effectiveness of the mission as practice for future exploration or as a scientific mission. Goals that supported industry interests were all that remained relatively intact. More generally, the burgeoning asteroid mining is, itself, likely to be locked in via infrastructural commitments. Despite claims that asteroid mining would support a diverse set of activities, the economics of the endeavor only seem possible when used as a resource for deep space exploration. An interdependence between asteroid mining and deep space exploration would make it difficult to reconfigure the way exploration is conducted. In the case of asteroid mining, both the mining operations and exploration activities would be dependent upon one another. Similarly, the current development of private spaceflight options suggests a dependence on the Falcon series of launchers, with the Vulcan launcher still uncertain. This reliance on a single launch vehicle series operated by a single company contributes to lock-in by ensuring a disproportionate dependency both on SpaceX's hardware and interests. Moreover, the spread of market ideologies throughout aerospace industries across the globe is indicative that such ideologies are also becoming locked in.

Lock-in refers to the way in which reliance or dependence can prevent alterations to a sociotechnical system based on learning by doing. This chapters has explored the ways in which a variety of sociotechnical components can become locked in; exclusion of interests that conflict with those of private industry, infrastructural dependence, dependence on specific companies and their technological artifacts, and exclusive use of market ideologies have all contributed to lock-in for private spaceflight. Lock-in alone, however, is insufficient to completely prevent the selection of alternatives. Could forces similar to those involved in lock-in be present when previously disregarded options begin to gain ground? Additionally, analysis of lock-in provides little information regarding the directionality of future development beyond the observation that such direction is being delimited. The next chapter supplements lock-in as a facet of obduracy with path dependence. By analyzing the dominant pathway of space development, chapter five will analyze the extent to which privatization does or does not support previously neglected pathways, as well as what pathways are being excluded from future consideration and by what forces.

5. Path Dependence

5.1 Introduction

The direction of technological development can sometimes seem autonomous. Previous decisions about technology can act to restrict available decisions in the present and the future. After the 1973 oil crisis, the United States instituted a policy of energy independence. While this might have come in the form of the development and implementation of renewable sources of energy, most of the gains towards so called energy independence were in domestic fossil fuel extraction. There was little preexisting investment and infrastructure: few manufacturers of wind turbines or solar arrays, few universities which prepared scientists and engineers for research and development on renewable energy, and there were too few small scale attempts at implementing renewable from which to model a national policy. However, the U.S. oil and gas industry was very well established and experienced. So innovations like more fuel efficient cars and new oil and gas extraction techniques made up the lion's share of American policy (Kemp, Rip, and Schot 2001). Despite the fact that regulators knew about the errors of fossil fuels, and even attempted to correct them, path dependence prevented a substantive correction. Future responses to challenges were exceptionally dependent on previous decisions which favored fossil fuel use. Path dependence focuses on the way in which present decisions exclude future options, just as past decisions have excluded contemporary options.

Previous chapters have analyzed how inattention to the constructive results of decision-making and overreliance on particular technologies and interest groups can inhibit learning and therefore prevent the adoption or consideration of alternatives. This chapter analyzes how sunk costs, unquestioned precedent, and generally governance structures that privilege economic values and the interests of private businesses erect barriers to reconstruction. Valuing cost effectiveness or an increased consumer base over goals such as safety or scientific value, or giving business executives a disproportionate influence over a public program are some examples of such values. What pathways are currently being pursued through private spaceflight? To what extent do these pathways exclude alternatives? On what basis have some pathways been selected and others excluded? How has a technical and economistic framing of space exploration contributed to path dependence?

In this chapter, I examine the current pathway of development for private spaceflight. The chapter presents a brief historical account showing the development of the current pathway. It then goes on to analyze the extent to which alternative pathways are available or excluded. This pathway was charted long before privatization became dominant, so the chapter ends with an analysis of the extent to which contemporary economistic governance reinforces this pathway or steers away from it.

5.2 Characterizing Path Dependency

Obduracy limits the available future pathways of technological development, thus creating a path dependence in which past and present decisions exert a gentle tyranny over the future. The idea that contemporary decisions have a limiting effect on future options is not new. For example, most people understand the concept of opportunity costs; each choice made precludes the potential benefits of a competing choice. Path dependency explores the same idea, but focuses on the potential consequences for re-choosing technological pathways in the face of clear errors. This chapter is concerned with what happens when the ability to adapt technological decisions is curtailed by the systematic exclusion of competing options. To what extent does path dependence limit the ability to identify, learn from, and respond to mistakes in technological development?

Social forces can contribute to path dependency on a grand scale. Alexis de Tocqueville theorizes that "democratic" and "aristocratic" societies follow divergent pathways of technological and scientific development. Democracy gives rise to more empiricism, while aristocracy affords more theoretical studies. Democracy leads to mass production of cheap useful goods while aristocracy leads to limited production of unique high quality goods (de Tocqueville 2000, 2:45–47). What de Tocqueville describes might be considered a form of path dependency, where the selection of a particular governance structure takes off the table pathways of technological development more strongly associated with competing structures.

Kranakis builds off of this theory by studying the development and construction of suspension bridges occurring simultaneously in France and America. She argues that great sweeping political structures such as democracy and aristocracy are mediated by more immediate social and institutional structures such as patent systems and community structure (Kranakis 1997, 2). The American engineer, Finley, wanted to make a profit licensing his suspension bridge design for use in America's many underdeveloped rural communities. Navier, the French engineer, wanted to design a bridge that would cement his legacy and improve his standing in a professional society that valued theoretical contributions. These differences altered their design, methods, and practical implementation, creating completely different pathways of bridge development which were, themselves, dependent on social structures and previous pathways of development in both nations (Kranakis 1989, 1997). The range of possible technological trajectories is dependent upon the historical and cultural context in which it takes place.

Kemp et al (2001) argue that "the development of new technology thus depends on characteristics of the existing technological regimes and the overall sociotechnical landscape" (276). These constraints may be both real and perceived. Sometimes they are cultural;

traditional ways of thinking may prevent some pathways from even being considered (Hommels 2005). Single-family housing is such a case. Most housing development in the United States after WWII was single family housing, reflecting particular American values like independence. But the dominance of multi-family housing developments during this time in many European nations, such as Sweden, shows that this trajectory could have been otherwise (Hommels 2005, 339–40). Other times they are structural; the patent system, for example, shapes design considerations such that some designs that would be possible under alternative legal configurations are not considered (Kranakis 1989). In such circumstances, these components circumscribe themselves into the pathway of technological development at the very level of design (Kranakis 1988). Thus, the limitations of path dependence can be borne out in physical artifacts, but can also be social, cultural, or psychological. Perception of choice is important.

Some degree of path dependence is inevitable. After all, it seems unreasonable to expect social and political forces to never limit available decisions and agendas. However, path dependence can become a problem if nearly all alternatives to a single pathway of development are excluded from consideration, as happened in the case of the American policy of energy independence after 1973. Without at least some available alternatives, it is difficult to envision changes that might improve current systems. Thus, path dependency is a direct barrier to the ability to improve spaceflight via trial and error.

In his book, Red Mars, Kim Stanley Robinson’s (1993) characters envision the potential to start anew on another planet and fix many of the mistakes of terrestrial society. Their failure to achieve this goal provides a good example of what path dependency might look like in terms of space exploration. The characters in this science fiction story rely on private companies to provide much of the resources necessary for the undertaking of Martian colonization. But this decision hampers them at every turn. These companies have a stake in the outcome, and this initial dependence on their resources gives them disproportional influence. In the book, this results in a war that kills millions. While these extreme consequences act as a literary device in the story, less severe, and more likely consequences may still occur. For example, such dependence on private companies for development might prevent terrestrial governments from protecting laborer's from poor conditions. Industry would also have disproportionate incentives to develop colonies quickly, thus increasing the likelihood and potential consequences of a mistake in the process. It is a clear example of how choosing to rely on private companies to conduct space development may prevent future citizens from making their own choices about what spaceflight should accomplish.

Such path dependency also limits the ability to adjust to unforeseen or unintended consequences. As the consequences of climate change become both increasingly clear and increasingly dire, many partisans may regret the history of fossil fuel development in the United States that now hampers those attempting to switch to renewable energy. What will terrestrial citizens do if we find, in the future, that our values for spaceflight have changed, but the over reliance on private companies at the early stages of development have hampered our ability to institute those changes? Will it be possible to respond if accidents are unacceptably high? If the broad benefits claimed by privatization partisans do not materialize, will it be possible to effect change so that space development benefits more people? If path dependence has sufficiently excluded the alternatives to private spaceflight, the answer to these questions is likely to be no.

Moreover, high degrees of path dependence limit the number of people who have influence over technological development, and thus denies citizens substantial influence over their everyday lives. These aspects of path dependency pose barriers to reconstructing technological systems in response to new information. As private spaceflight stands to launch a new push in space development, does it minimize, or increase path dependence? What are the current trajectories? What are the alternatives? And were those alternatives fairly considered or are they being crowded out by contemporary policy?

5.3 Defining the Current Pathway

Providing historical context is necessary for understanding contemporary exploration pathways and analyzing the robustness of potential alternatives. For path dependency, history matters. Just as in the U.S., the history of frontier expansion led to the development of patent law that encouraged practical, accessible, and marketable designs (Kranakis 1989), historical preferences in spaceflight are likely to influence what destinations and development pathways seem feasible today. While a fully comprehensive history of space exploration is too broad in scope for this dissertation, analyzing key contributions to the exploration of Mars can provide insight into why Mars is the destination of choice for private spaceflight executives today. What factors make Mars such an enticing destination? What decisions and factors maintained Mars as a favorable pathway, even as scientific discovery revealed it to be inhospitable? How does the pathway toward Mars manifest today?

Although the planet Mars has been known and tracked by many ancient peoples (Hogan 2009, 6), contemporary interest in Mars stems from its potential *habitability*. When Schiaparelli first identified the "canals" on Mars, he personally stressed that this interpretation was the most unlikely of the various possibilities for the formation of the canal like structures. But the image of artificial canals crisscrossing the surface of the planet was so compelling that another scientist, Lowell, claimed that a Martian civilization had marked the face of the planet with a massive network of fantastic canals. His claim had limited scientific credibility, but ignited the public imagination of Martian life (Hoyt 1976, 12; Wilford 1991, 23–30). Contemporary notions of Mars harboring life began here, and continue to be influential in deciding on development pathways for spaceflight. From the get go, Mars was meant for colonization.

Because of this initial interest sparked by the idea of alien life, Mars took on a sizeable contemporary cultural significance. Very early on, Mars was not just Mars, but a way for partisans to project their own visions for a desirable future, or their fears of an undesirable one. Three years after Lowell's publications, HG Wells published the science fiction book *War of the Worlds* in 1898 (Wells 1898). In 1917 Edgar Rice Burroughs published *Princess of Mars* and the public image of Mars as our inhabited neighbor became thoroughly established (Burroughs 1917). This genre of science fiction was revitalized in 1938 with the radio adaptation of *War of Worlds* done by Orson Welles (Welles 1938), and the full length *Flash Gordon* movie in which Flash Gordon saves the world from a Martian invasion (Beebe, Hill, and Stephani 1939). On the eve of World War Two, Martians became a substitute for the looming threat of fascists in Europe. After the war, the red planet changed as a stand in for the red scare. In 1949 Robert Heinlein published *Red Planet* (Heinlein 1949). A year later in 1950, Bradbury authored *The Martian Chronicles* (Bradbury 1950) and the film *Rocketship X-M* depicts the discovery of an ancient Martian civilization destroyed in a nuclear holocaust (Neumann 1950). In 1951 astronauts again thwart a Martian take-over plot in the movie *Flight to Mars* (Selander 1951), followed by the film adaptation of *War of the Worlds* in 1953, again thwarting Martian takeover (Haskin 1953). Finally, in 1959 audiences watch the film *Angry Red Planet* (Melchior 1959). If Mars was inhabited, perhaps those inhabitants were like us. This idea of cultural similarity stemming from the scientific possibility of habitability allowed Mars to act as a blank canvas on which partisans could project their politics. These works both contributed to and are evidence of the connection between Mars's cultural significance its habitability.

The line between science fiction and science is often blurred, and in this case even the scientific study of the red planet has been somewhat steered by these cultural projections of what a good future might or might not look like. NASA scientists viewed the habitability of Mars as a lens through which they might discover the origin of life and learn about ourselves, thus beginning the pursuit of Mars as the dominant pathway for space exploration. It was von Braun’s influential ideas about Martian exploration that popularized Mars as a destination for exploration for the scientific and engineering communities within spaceflight. The culmination of von Braun’s several influential popularizations of space exploration was always the human colonization of Mars[9]. This vision has become the assumed pathway for human spaceflight and space exploration. After Sputnik, “once the concept of robotic planetary exploration was conceived during the coming years, it was taken for granted that Mars would be a priority” (Hogan 2009, 11) largely due to the influence of von Braun on the priorities of the American space program. Recall the contribution the accumulation of policy had on the creation of lock-in, and it seems unsurprising to find that this sort of cultural accumulation around the significance of Mars also contributes to the limitation of other future pathways.

But the first exploration missions to Mars returned data that flew in the face of the very assumptions about Mars that justified those missions in the first place. In 1964 NASA launched its first Mars mission, Mariner 4, for a flyby mission to Mars. It did not find life. Mariner 4 sent back pictures of a barren, relatively unchanging surface. The sensors indicated a very thin, carbon dioxide atmosphere and no protective magnetic field (Hogan 2009, 11–12). Even von

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[9] See Chapter 3 on “Accumulation” for more detail on von Braun’s popular publications.

Braun had expected a Martian civilization, or at least some form of life. Overall, the data presented by Mariner showed a planet hostile, rather than hospitable, to life. This first mission sent back data that contradicted the reason for interest in the planet.

But NASA was dedicated to this pathway, and continued to send missions until they found data that justified its continuation. Between 1969 and 1972, NASA also sent Mariners 6 and 7 on flyby missions to Mars, and Mariner 9 to orbit. It wasn't until Mariner 9 that NASA finally got data of interest. It showed the great mountain Olympus Mons, and the deep crevasse of Valles Marineris, as well as river-like channels near the polar regions (National Aeronautics and Space Administration 2017) all of which indicated scientifically interesting geological activity and the potential for water, and therefore life, in Mars's ancient past. In 1975, NASA launched the first successful Mars landers, Vikings 1 and 2. These operated from 1976 to 1982 and were designed primarily to test for the possibility of microbial life on Mars. However, the chemical and biological analysis of the soil on Mars by the Viking landers indicated no signs of life on the red planet (Bob Allen 2015; Williams 2016). NASA was pursuing the pathway of Mars exploration despite initial findings indicating that the selection of this pathway may have been on a false premise. Had NASA been taking a trial and error approach, they might have diversified their planetary studies to find other possibilities for habitation rather than double down on the particular pathway towards Mars.

More recently, this exploration effort has expanded even further, with an enormous number of missions. Although after the Viking missions NASA sent no new missions to Mars for over a decade, in 1993 NASA formed the Mars Exploration Program (MEP) to examine the habitability of Mars, including the possibility of existing life, climate, and natural resources (Shirley and

McCleese 1996). This new initiative resulted in several Mars missions. Table 1 shows a history of all of NASA's Mars missions to date and gives some brief information on each one.

Table 5.1: Table describing all NASA missions to Mars.

Mission Name	Launch Date	End Date	Mission Type	Description
Mariner 3	November 5, 1964	N/A	Flyby	Payload fairing failed to separate.
Mariner 4	November 28, 1964	N/A	Flyby	Pictures of a dead world changed the scientific community's vision of life on Mars.
Mariner 6	February 25, 1969	N/A	Flyby	Confirmed findings of Mariner 4.
Mariner 7	March 27, 1969	N/A	Flyby	Confirmed findings of Mariner 4.
Mariner 8	May 9, 1971	N/A	Orbiter	Failed to Orbit
Mariner 9	May 30, 1971	October 27, 1972	Orbiter	Discovered Olympus Mons and Valles Marineris and evidence of water erosion.
Viking 1	August 20, 1975	November 13, 1982	Lander	Search for microbial life in soil, results negative.
Viking 2	September 9, 1975	April 11, 1980	Lander	Search for microbial life in soil, results negative.
Mars Observer	September 25, 1992	N/A	Orbiter	Lost communication.

Mars Global Surveryor	November 7, 1996	November 2, 2006	Orbiter	Mapping mission designed to enable future Mars landers and rovers.
Mars Pathfinder and Sojourner	December 4, 1996	September 27, 1997	Lander and Rover	Conducted atmospheric and soil tests, and tests new landing method on notoriously difficult Mars.
Mars Climate Orbiter	December 11, 1998	N/A	Orbiter	Entered Martian atmosphere rather than Mars orbit due to unit conversion error.
Mars Polar Lander	January 3, 1999	N/A	Lander	Failed to land.
Mars Odyssey	April 7, 2001	N/A	Orbiter	Searches for evidence of past and present water, and serves as a communication relay for Mars landers and rovers. Still operational.
Mars Exploration Rover Spirit	June 10, 2003	March 22, 2010	Rover	Analyze Martian geology and surface features. Operated 20 times longer, and drove 13 times further than originally designed.
Mars Exploration Rover Opportunity	July 8, 2003	N/A	Rover	Same as Spirit, but still operational.
Mars Reconnaissance Orbiter	August 12, 2005	N/A	Orbiter	Primary purposes to monitor weather patterns and surface conditions and study potential landing sites for future Martian missions. Still operational.
Phoenix	August 4, 2007	November 2, 2008	Lander	Designed to test for the suitability of microbial life and research the history of water on Mars.
Mars Science Laboratory Curiosity	November 26, 2011	N/A	Rover	Search for microbial life, investigate role of water, planetary habitability studies in preparation for humans. Still operational
MAVEN	November 18, 2013	N/A	Orbiter	Study the Martian atmospheric evolution and potential impact of ancient life. Still operational.

Table 5.1 shows a long list of missions to Mars, many of which are designed either to facilitate future missions or to study the habitability of the planet. This sheer volume of missions demonstrates how important NASA considers the study of Mars, especially since the beginning of the 1990s. During this time, the MEP created an ever increasing focus within planetary science on the study of Mars. Recently, missions have explicitly prepared for future human missions, a goal that was politically untenable for over a decade after the Viking missions.

The funding allocations for NASA planetary science also support the thesis of Mars's importance. Figure 5.1 shows that since 1998, Mars has represented the single biggest funding category within planetary science and that since 2003 Mars has consistently taken up greater than 20% of the planetary science budget[10]. Most planetary scientists will tell you that Mars is where the money is. If funding reflects priorities, then Mars is clearly a research priority for NASA. Few resources are dedicated to studying potential alternatives.

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[10] Before 2005 planetary science, astrophysics, and heliophysics were grouped together in funding reports. This figure represents the author's best attempt to decouple astrophysics and heliophysics missions from total planetary science funding.

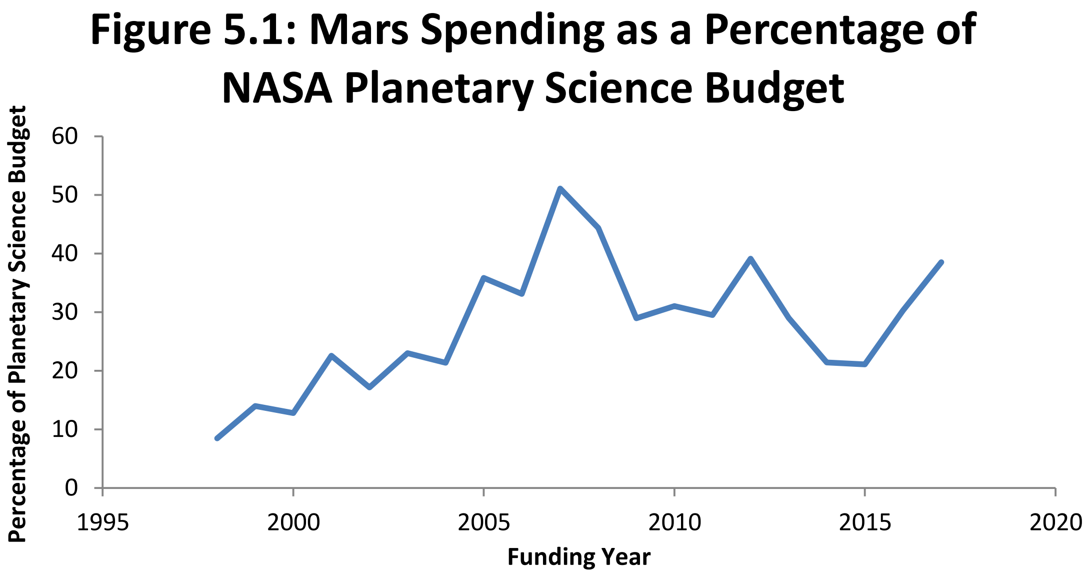

Figure 5.1: Chart of Mars Spending as a percentage of the total Planetary Science Budget at NASA from 1998 to 2017.

Planetary scientists and NASA administrators have engaged in a concerted effort to soften up policy makers to the possibility of human missions to Mars (Hogan 2009, 16–35). Path dependence in this case is created by powerful actors who benefit from the status quo. The first such effort conducted by von Braun has already been described. But contemporary softening up started as early as 1981 with the Case for Mars conferences. At this conference, affectionately called the "Mars Underground," the organizers and participants viewed Mars as "the next logical step for the space program because the Martian environment provided resources that could be utilized for *in situ* manufacturing of life support materials" and that Mars is "a natural evolutionary step of space development" (Hogan 2009, 26–27). This group sought to get others to invest in the Mars pathway.

The Mars Underground conference was successful, inspiring a whole new set of advocates for Mars exploration. A notable member of the Mars Underground was Robert Zubrin. Inspired by his interactions at these conferences, he published a book by the same name in 1996: *The*

Case for Mars (Zubrin and Wagner 1996). As the Mars Underground conferences came to an end, Zubrin founded the Mars Society in 1998 to continue with their mission. Now the largest space advocacy group outside of industry, the focus of the Mars Society is primarily in public outreach and political advocacy for the human exploration and settlement of Mars ("The Mars Society" 2015). Several other organizations exist that support the objective of human settlement of Mars. The Mars institute, based out of NASA Ames Research Center focuses on the scientific research necessary to advance the human settlement of Mars ("About the Mars Institute" 2014). The Mars Foundation focuses on outreach, educational, and research projects culminating in a Mars homestead ("Our Mission" 2017). This proliferation of advocacy groups both demonstrates how well-established the Mars pathway is already, and also the resources being marshaled to further entrench it.

NASA has also spent a great deal of effort normalizing Mars exploration directly. During the 10 years in which NASA was not conducting new Mars missions, they were instead focusing on a policy agenda in support of this goal. In 1984, after Congress directed President Reagan to appoint a National Commission on Space development to develop a long term spaceflight agenda, Reagan appointed Thomas Paine to head the commission. The commission authored a report in 1986 that outlined a plan for development of space resources in support of human exploration. These recommendations focused heavily on the extraction of resources as a principal long-term goal of space exploration (United States National Commission on Space 1986). In so doing, Paine's report provided the basis for the potential profitability of space exploration, which would become a foundational argument for expanded Martian exploration.

Although the reception of this report was not particularly enthusiastic, NASA continued their strategy of softening up policy makers through a continuous emphasis on Mars exploration.

Later that year NASA Administrator James Fletcher assigned former astronaut Sally Ride to chair a task force to respond to the commission's report. An immediate program for the human exploration of Mars was one of four potential options presented, the others being "Mission to Planet Earth," "Exploration of the Solar System," and "Outpost on the Moon." Although the report emphasized these other three options, it still portrayed them in terms of an "inexorable" progression towards the red planet (Ride 1987) in keeping with the incremental strategy of softening up. In response to the reception of the first report, NASA's second report simply expanded the time frame in which humans would gain the resources locked away on Mars, rather than search for an alternative goal.

The reports favoring the Mars pathway continued to accumulate. In 1987 Administrator James Fletcher establishes the Office of Exploration at NASA, and the first thing the office did was conduct a study building on the reports already done by Paine and Ride. The report, submitted in December of 1988, again focuses on missions to Mars. The case studies presented as potential missions were a mission to Mars's moon Phobos as a stepping stone to a crewed Mars mission, a direct human mission to Mars, a Lunar outpost as a springboard for Martian exploration, or a crewed scientific research station on the Moon (NASA Office of Exploration 1988). The report focused on a policy of "evolutionary expansion…that would concentrate more on permanence and the exploitation of resources" (Hogan 2009, 33). These reports mark the most recent additions of a cultural paradigm for Mars exploration.

The persistent cultural tradition established through this accumulation towards Mars now acts as a driver for its continuation. Once an idea becomes culturally engrained, it can direct development as a persistent tradition. Consider the area of urban design. The designs of railway stations and subway infrastructure in cities like New York and Washington D.C. were all set, in part, by shared cultural visions of what urban spaces should be by proximate decision makers (Hommels 2005, 340–41). In much the same way, the cultural paradigm of Martian exploration, including scientific studies about its similarities with Earth, public imaginaries, and political softening up, continues to influence how contemporary actors view space exploration and development. But how has this cultural tradition influenced private development? As spaceflight shifts towards a more market oriented approach focused on economics, how does this culture translate?

Contemporary private companies continue to build on the foundation set by NASA's softening up campaign, continuing the persistent tradition of Mars exploration. "The aerospace community rarely agrees on anything, but pretty much everyone accepts that the next 'mountain' for human explorers to climb involves the fourth planet in the solar system" (Berger 2016b). Elon Musk is perhaps the most obvious example. Musk has made clear in a presentation outlining his Mars colony ship that his goal is to make life multiplanetary (Musk 2016). This is not a new motivation, and Musk has written about and stated in interviews that he founded SpaceX specifically to achieve this goal (Musk 2009; Urban 2015). At least Musk and his company, SpaceX, are not interested in exploring alternatives to the Mars pathway.

Musk's SpaceX is far from the only private company with an interest in the red planet. Boeing, a major aerospace company with a long history contracting for NASA and the military as well as the only other company to hold a commercial crew contract aside from SpaceX, announced following Musk's September presentation that they will beat SpaceX to Mars (Muilenburg 2016). Jeff Bezos has also announced that his company, Blue Origin, is developing a new launch vehicle, the New Glenn, which will facilitate Martian travel via a Moon first approach (Bezos 2017). The private spaceflight industry does not seem to be altering the trajectory towards Mars.

Space exploration has become synonymous with a pathway to Mars. Much of planetary science, NASA's political negotiations, and even plans for private space development have been oriented towards the singular goal of sending humans to Mars. Many actors view Martian settlement as inevitable, and even programs that are not directly related to the study of Mars are often framed as building up the capabilities or understanding necessary for Martian exploration.

5.4 Where else to go?

But why go to Mars? Or perhaps the better question is, why not go to some other destination? Path dependency can be a problem because it acts as a barrier to being able to select alternatives in the event that any unintended consequences prove too harmful to endure. Recall the trouble switching to renewable energy after the oil crisis of the 1970s. Even with strong economic incentive to switch, path dependency inhibited the success of alternatives to fossil fuels (Kemp, Rip, and Schot 2001). Could a different pathway be selected if human travel to Mars proves elusive, less useful than anticipated, or even harmful? To what extent, and which, alternative pathways for space development are being excluded? What makes Mars seem like the only viable option?

To answer these questions, this chapter begins by analyzing the ostensible motivations for Martian exploration and colonization. Such motivations can be important indicators of the extent of path dependence. In Kranakis's (1989, 1997) study of the French engineer Navier's suspension bridge project, the bridge was ultimately never built due to exorbitant costs. His motivations were to use the project to demonstrate his scientific and theoretical acumen in order to advance within his scientific society. At this he was successful due to the many mathematical contributions he made to understanding suspension bridge behavior, even if these contributions never manifested themselves in a successfully implemented design. Navier's motivations excluded the more practical approach of his American counterpart, Finley, and were strong enough to resist alternatives, even as the bridge project itself failed. Are there parallels between this scenario and contemporary private development towards Martian exploration? What are the barriers to selecting an alternative pathway? By what rationale have those alternatives been excluded? How might these barriers be overcome?

Martian colonization is often portrayed as a way of saving humanity. For Zubrin and the Mars Society, it opens a frontier that saves humanity from "cultural homogenization" and "technological stagnation" (Zubrin and Wagner 1996, 195–97). Elon Musk argues that Mars will serve as a backup in case some disaster, natural or human-made, destroys human civilization on Earth (Urban 2015; Musk 2016). In general, Mars ensures the longevity and success of humans as a species by diversifying where the species lives.

This sort of goal could be achieved through any pathway towards multiplanetary life. So why Mars, specifically? Mars is purported to be uniquely technically feasible on relatively near term time scales, and uniquely capable of sustaining relatively large populations. The historical association between Mars and habitability lends strength to these arguments. Musk has argued that, despite its challenges, Mars is easier to colonize than any of the other terrestrial planets or the moons of the gas giants. The technology for any of these other endeavors does not exist while the technology to send humans to Mars already exists. He has also argued that, while it is feasible to create a permanent settlement on the Moon, such a habitation would be perpetually dependent on supplies from the Earth. Musk's claim is that Mars is the only location in the solar system capable of supporting enough people to be self-sufficient, a number he estimates to be around one million (Urban 2015; Musk 2016). Thus the ostensible reason why Mars has been selected as the destination for colonization is because it is the most technically feasible location to achieve the large populations necessary. How do these claims hold up under scrutiny? Is Mars the only feasible option?

First, are one million people really necessary to accomplish the goal of species preservation? Anthropologists and biologists have utilized the concept of the minimum viable population for some time to describe the statistically minimum population needed to avoid extinction and maintain a healthy gene pool. Estimates of this number for humans are wide ranging. The smallest estimate for the number of people needed to sustain a multigenerational interstellar ship for 200 years and ten generations is 160 people (Kondo 2003). Estimates taking into account other large mammals average about 4000 (Traill, Bradshaw, and Brook 2007). The highest estimate accounts for technical specialization necessary to run an industrialized colony, and suggests a minimum of 10000 individuals, but notes that 40000 is the smallest population that also protects substantially from natural catastrophes (C. M. Smith 2014). Even this largest estimate is 25 times smaller than Musk's estimate. So it would seem that, at least, Musk's population estimate justifying Mars colonization as the only viable pathway for space development is incomplete at best.

Could the Earth's other planetary neighbor, Venus, be feasible for supporting these populations? Venus typically conjures harsh images as the inhospitable outcome of millennia of runaway greenhouse effect. The surface temperature, averaging 872 degrees Fahrenheit (467 degrees Celsius) is hot enough to melt lead, and the atmospheric pressure, 90 times higher than sea level on Earth, is equivalent to being one kilometer below the surface of the ocean. Add to that an unbreathable atmosphere and the sulfuric acid rain and Mars starts to look like a paradise in comparison. However, human missions to Venus may be just as technically feasible as those to Mars, given the right mission design.

NASA’s High Altitude Venus Operational Concept (HAVOC) has developed a mission plan that takes advantage of the relatively mild conditions above the sulfuric acid clouds, about 50km above the surface in Venus’s atmosphere (Reeves and Payan 2016). The report argues that Venus offers advantages to feasibility over Mars in the areas of environment, ‘landing’, and interplanetary travel.

First, the feasibility of addressing environmental hazards is comparable between Mars and Venus. At this altitude, temperatures average 167 degrees Fahrenheit (75 degrees Celsius), while on Mars surface temperatures average -81 degrees Fahrenheit (-63 degrees Celsius). Neither temperature is healthy, but both roughly align with the extreme temperatures possible on Earth and represent comparable challenges. In many other aspects, however, designers would have an easier time preparing for a Venus mission. The atmospheric pressure at that altitude and the gravity on Venus are almost identical to that on Earth (Arney and Jones 2015). Mars, on the other hand, has 1/100 the atmospheric pressure of sea level on Earth, and approximately one third the gravity, which can lead to severe musculoskeletal degeneration. Despite having no magnetosphere, Venus’s atmosphere provides substantial radiation shielding so the exposure is about equivalent to living in northern Canada (Arney and Jones 2015). An unshielded astronaut on Mars would be subject to 40 times the radiation dosage per day of the average American, a dangerous amount. A solar panel at that altitude on Venus would generate about 1.5 times as much energy as a solar panel on Earth, but on Mars it would only generate half as much (Arney and Jones 2015). Comparing some of the conditions in the Venusian atmosphere to those on Mars shows some design challenges may be easier for a Venus mission than one to Mars.

Second, travel to Venus can be quicker and easier than to Mars. Thus, sending humans to Venus rather than Mars reduces the exposure to risks such as time spent away from gravity and from radiation protection. The absolute minimum duration of exposure to zero gravity and interplanetary radiation levels for any mission to Mars would be 500 days, including a 30 day surface mission (Ackerman 2014). This is because Mars and Earth only approach each other every few years, and the distance of this closest approach actually fluctuates between instances. Venus, on the other hand, is much closer and has a more regular closest approach to Earth. It would take 110 days to travel to Venus, and another 300 to travel back after a 30 day stay. Thus, the shortest mission to Venus is 440 days, which is 60 days, or two months, of reduced exposure compared to Mars (Lugo et al. 2015).

Finally, "landing" for the HAVOC mission may be easier than on a mission to Mars. Floating a craft in the Venusian atmosphere is surprisingly easy. Because the atmosphere is so thick, lighter than air flight on Venus can be achieved with an oxygen/nitrogen mix (i.e. the composition of the atmosphere on Earth) (Lugo et al. 2015). In other words, the habitat itself would be buoyant. There is also no need to calculate a complicated entry trajectory to reach the landing location, because the craft would not need to land. Landing on Mars has clearly been done before, but only with a historical 50% success rate (NASA Mars Exploration n.d.). Mars gravity is strong enough that a crash landing would destroy the landing vehicle, but the atmosphere is too thin to rely on aero braking or parachutes as is done when landing on Earth. The solutions for autonomous mission have been elegant. Mars Science Lab was lowered via sky crane: an umbilical that lowered the rover from the landing vehicle, which then used the last of its fuel to pitch and thrust away once the rover touched down so that, when it crashed, it would not damage the rover (NASA Jet Propulsion Laboratory n.d.). Mars Pathfinder, consisting of the Spirit and Opportunity rovers, utilized airbags which inflated to cushion the crash into the surface, and bouncing the landing vehicle up to 12 meters high, and 200 meters away (National Aeronautics and Space Administration n.d.). Such solutions are undesirable for human passengers that want to survive.

Beyond Venus, there are several other potential options for space development which are also feasible. One proposal utilizes the planned development of asteroids and comets. By extracting materials from the interior rather than the surface, a space mining operation simultaneously creates the location and the resources for a colony. Such a colony could be sustained on the resources within an asteroid or comet for an extended period of time, probably long enough to create a more developed economy that would allow the colony to trade for what it needs easily. Being located within the asteroid or comet protects the residents from harmful radiation. Gravity could be simulated by spinning the asteroid or comet, and the whole endeavor is feasible using contemporary technology (Kecskes 2002; Charania 2008). Such colonies would also be smaller scale than colonizing a whole planet, thus reducing the severity of the consequences of failure. Additionally, being closer to Earth than Mars, they would reduce the dangers from spaceflight itself and responding to potential errors would be easier than a Mars colony. Asteroid and comet colonies are a feasible alternative that deserve exploration.

It may not even be necessary to colonize an existing body. It may be possible to build colonies from scratch. NASA conducted two studies during the Apollo program examining the feasibility of constructing so-called free space colonies at Lagrange points. Both studies found that creating such free space colonies was feasible using Apollo era technology (O’Neill 1977; R. D. Johnson and Holbrow 1977). Such colonies are therefore likely to at least as feasible today, if not more-so. There are several alternatives to Mars.

If NASA officials know that other options are feasible, why does Mars remain so dominant as the pathway for future development? One factor may be that, compared to all other potentially feasible options, Mars has been for more thoroughly studied. To understand how learning about an option might bias decision-makers towards its selection, we might examine the multi-armed bandit problem. In this problem, a gambler is faced with a row of slot machines with different probabilities and payouts. They start with no information, and must try the slot machines to figure out what the payoff is for using each machine. Clearly, the best possible outcome would be to select the machine with the best payoff first, and play no other machine. But in this situation, the gambler doesn't know the machine they are playing has the best payoff because they wouldn't try any other machine. In other words, the problem lends itself to exploiting machines with known payoffs rather than exploring to improve the probability that the machine used has the highest payoff. Unless exploration is forced, for example, through a method that requires some percentage of tries to be on new machines, the multi-arm bandit problem will quickly result in the gambler only using one machine. Once they learn enough to know the machine has a positive payoff, the incentives for trying other machines are drastically reduced. It is likewise with selecting a pathway for space exploration. The more scientists learn about Mars, the better it seems for colonization, but unless policymakers implement a policy of exploring other options, many groups are likely going to miss out on the potential benefits of alternative destinations.

There have been many historical examples elucidating the potential consequences of such dedication to particular technological trajectories without thinking about their potential harms. During the heyday of atomic energy, experts thought this new technology would usher in a new age of peace and prosperity. Many people are familiar with the failed prediction of "energy too cheap to meter," but many other proposals were extremely risky in hindsight. Project Plowshare examined the potential of nuclear explosions for construction, which included a proposal to widen the Panama Canal using nuclear weapons. One can only imagine the fallout from that radiation ("Interoceanic Canal Studies 1970" 1970). Atoms for Peace intended to promote international peace and cooperation through nuclear power, but ended up heightening tensions in the cold war as a driver for the proliferation of nuclear weapons (Hicks 2014). In these examples, dedication to a particular technological trajectory caused or very nearly caused substantial but needless harms to millions. Dedication to a particular trajectory of space development may have the same outcome without maintaining a diversity of potential alternatives.

Based on this analysis and the conclusion of the previous section that Mars's predominance in space exploration is cultural and historical, built up through intentional political strategies by proponents rather than purely scientific or technical, could Venus, asteroids, or Lagrange points seem more amenable to colonization had they been more thoroughly studied? Previous decisions and preferences have lead to the problem where exploring Mars seems inevitable, partly because it is so well studied compared to other options. Part of the reason why Mars seems like such a good option is because comparatively little time and few resources have been spent examining alternatives. How could anyone be expected to make good decisions about potential spaceflight destinations under such conditions?

The uneven distribution of resources towards some potential pathways compared to others is a clear barrier to learning. Although perfect information is clearly impossible, it should not be controversial to suggest that private executives and NASA administrators make decisions about space development pathways having an equal understanding of at least a multiplicity of options.

Given this, two questions which logically follow are: How can decision makers generate multiple potential options from which to choose? And what incentives might promote the relatively equal treatment, at least initially, of these different options?

An important factor in answering both of these questions is likely to originate in the political concept of pluralism. Pluralism is the idea that a democracy consisting of several competing interest groups with relatively equal power will maintain a democratic equilibrium in which no one group is able to exercise complete control over the others. Thus, pluralism ensures the ability of citizens to participate in decisions about their own lives while protecting against their suppression (Dahl 1956; Held and Krieger 1984; Dahl 2006). Charles Lindblom's (1965) contribution to pluralist theory is especially useful for thinking about the mitigation of path dependency. Lindblom argues specifically that democratic pluralism, under the right conditions, could produce more intelligent decisions because it prevents any one group from circumventing trial and error learning in favor of their own interests. In this case, pluralism might mean a plurality of options which experts explore, rather than the narrow focus demonstrated so far.

A more pluralistic system would need to incentivize a diverse set of options. One method which might yield this increased diversity would be to increase resources to less obvious potential development trajectories. This might follow the suggestion of Woodhouse (Woodhouse and Patton 2004; Woodhouse 2013) who suggests substantial advisory assistance to interested partisans who lack the resources to compete in decision-making. It might also take the form advocated by Pielke (2007) in which experts take the role of "honest brokers of policy alternatives," advocating not for one of some number of existing options but for options not otherwise considered that their expertise uniquely positions them to explore. Another possibility could simply be to allocate resources in such a way that privileges exploration of options rather than immediate payoff.

To ensure such a distribution of resources, other mechanisms must be in place to prevent widely shared conflicts of interest. One such method could be multi-partisan monitoring of various potential development trajectories. Such a strategy can speed up the learning process, expediting the discovery of errors and reducing the resistance to change in response to those errors (Woodhouse and Nieusma 1997). As an example in space development, if decisions about planetary research were left to scientists today, it is likely little would change. Since more scientists in planetary science study Mars than any other body, they would likely advocate more study of Mars. Including other groups with conflicting interests would prevent closing down research into other options before understanding their benefits and costs.

Although it may be that going to Mars is still the most desirable option, the articulated justifications analyzed so far have not been sufficient to exclude the pursuit or consideration of alternative options. That such exclusion has occurred, as already evidenced by the persistence of the cultural history of Mars, and the continued influence of that tradition within both public and private programs, suggests that path dependence may be a barrier to considering potentially useful alternatives. But if feasibility or population goals do not justify the selection of Mars, then what criteria are proximate decision makers actually using?

5.5 Economy Driving Pathways

While the previous section discussed the ways in which economistic thinking limits possible development trajectories for outer space, this section will consider the ways in which economistic thinking and control of development by executives is, itself, becoming path dependent. If a variety of pathways are, using current understandings, equally feasible, why do private spaceflight executives like Musk advocate for a trajectory based on Mars colonization? Path dependence is not just coincidental to decision-making, each pathway is a trajectory that benefits some people at the expense of others. So, another question is, what do private spaceflight executives hope to gain from Martian development? Equally as important, what potential benefits are average citizens missing out on if executives are allowed to determine the trajectory of spaceflight?

Elon Musk has framed the issue of Mars colonization as one of economics. He argues that two things are necessary to get to Mars: motivation to do it, and a method to manifest that motivation. Since humans have yet to go to Mars but, he argues, sufficient motivation to go does exists, the problem must be insufficient method. But, technologically speaking, rockets have had the capability to reach Mars for some time, so the problem with the method isn't technological, it's economical (Musk 2009; Urban 2015). NASA estimates that the total cost for a program to send a small crew to Mars would divide up to about $10 billion per crew member. The list of organizations or people that both have the desire to go to Mars and that kind of funding consists of one entry: NASA (and even they may not get the necessary monetary support from Congress). Musk believes that there needs to be more overlap between the list of people who want to go to Mars, and the list of people that can afford it. He proposes that the best and easiest way to achieve this is to decrease the costs so that more people can afford it (Urban 2015; Musk 2016). Musk's plan systematically eliminates technical and social barriers, leaving only economic ones to overcome, clearly a strategy that benefits a private company that stands to benefit economically as well.

Musk may be the only one to articulate so clearly these motivations, but others share them as well. Blue Origin shares many of the technological and economical goals of SpaceX. They implement similar innovations such as vertical takeoff and landing to improve reusability and increasing the size of their launch vehicles to increase capacity, all innovations focused on lowering the cost of spaceflight (Blue Origin 2017). They too have set their sights on Mars. Bigelow Aerospace has focused on developing and marketing lighter weight, cheaper to manufacture space habitats and space capsules to reduces the costs of spaceflight. They have partnered with SpaceX to launch their inflatable modules and to conduct joint marketing to international customers (Grantham 2012). Bigelow has also partnered with Boeing in the production of the CST-100 capsule for the Commercial Crew Development Program (CCDev) (Thompson 2012; "Crew Transport" 2016). Boeing's CEO himself has indicated that their strategy for beating SpaceX to Mars revolves around leveraging markets opened up by the reduced costs of spaceflight (Muilenburg 2016). A variety of established and new private sector actors demonstrate, through their actions, a vision of space development and exploration consistent with Musk's. Many executives clearly view Martian development as potentially profitable.

Even companies not directly involved in Mars exploration seem to be on board. Because private interests are driving the path dependency of Martian development, the interest in Mars and the interest in economistic spaceflight are somewhat intertwined. Other companies, such as Planetary Resources and Deep Space Industries (DSI) are also attempting to contribute to the reduction in spaceflight costs. Although representatives from neither company have endorsed Mars as explicitly as Musk has, their contributions to economical spaceflight are likely to be very important to an economically driven colonization of Mars. Many estimates of the low costs of spaceflight in the future assume a price for resources that precludes launching them from Earth, and therefore requires companies like these to successfully procure resources from extra-planetary sources. Private spaceflight executives are simultaneously supporting a Mars oriented space program and a space program centered on economistic values.

Mars is unique because of the resources readily available, enough to support a large economy, rather than because of its feasibility. Musk has said, “With the economic forcing function of interplanetary commerce, there will be the resources and the incentive to massively improve space transportation technology, and I think then things really go to a whole new level” (Urban 2016). This statement is particularly revelatory to the underlying motivations for the selection of Mars. Mars uniquely provides the basis for the commerce necessary to drive Musk’s “economic forcing function.” Musk is talking about the technical feasibility of large scale resource extraction, utilization, and trade, not the feasibility of colonization. Musk estimates that one million people is the minimum number to support commercial and economic growth large enough to create his “economic forcing function,” not that it is the number necessary to carry on human existence. So, although the ostensible reasons supporting Mars colonization are preservationist, the real driver for executives like Musk seems to be the enormous economic advantages for early movers.

In all likelihood, pursuing a Martian exploration pathway due to economic motivations will have major benefits for some small group of privileged business leaders, but most people will see marginal or no real benefits. While Navier achieved his goals of prestige and making mathematical contributions to suspension bridge design, these motivations meant that completing the bridge he was designing was merely secondary (Kranakis 1997). So while Navier was successful, he never helped a single person cross the Seine. The same seems likely for space exploration when the motivation is economical.

The companies conducting space exploration are likely to experience economic gain: from support industries, consumption of goods in the colonies themselves, and interplanetary trade at least. If public space programs become dependent on private spaceflight companies, then those companies will be obligatory passage points for access to space. When people begin to live in space, they too will be dependent on those companies. Not just for access to space, but for the very supplies and equipment necessary to survive. Such dependence will make it nearly impossible to resist decisions made by these private companies. In the same way that politicians already prioritize the interests of business leaders due to fears of economic repercussions (Lindblom 1982), or kept the space shuttle flying well after its safety issues were know because satellites were dependent on the launch system, politicians may also be loath to place Mars colonists in jeopardy by opposing the interests of private spaceflight companies.

Public benefits, on the other hand are likely to be slim. Some people might benefit from employment, although how many will have to uproot to another planet to take advantage of this benefit? Some have claimed that taking advantage of space-based resources will alleviate environmental degradation from terrestrial extraction (Hlimi 2014; MacWhorter 2015). However, these arguments don't account for disposal of these resources or potential increases in consumption as a result, and the economic viability of space-based resources being used on Earth is still in question.

Furthermore, a space program focused on economics is unlikely to be capable of meeting any public goods which cannot be monetized. In other words, it inherently limits the positions which can be represented. For example, there is little economic incentive for executives to advocate for planetary protection. Musk himself has dismissed concerns about contamination of the Martian environment with Earth based microbes (Berger 2015). However, once Mars is contaminated, it will be impossible to discern whether any life discovered there is native, or terrestrial. The potential discoveries regarding the origins of life are being excluded from consideration without advocates getting a say in the process. Any other such goods that don't translate well into profits are likely to be ignored in the same way.

Space development could have more equitably distributed benefits given other pathways. Consider some suggested geo-engineering projects in response to climate change. Proposed projects range from altering cities to be more reflective, to seeding the atmosphere with solar radiation reflecting aerosols, to building a space-based sun shade (Vaughan and Lenton 2011). The problem with such projects is that the uncertainty is excessively high, and the potential consequences are catastrophic. One way of mitigating these problems would be to gradually scale up these projects to observe and account for any unintended consequences (Woodhouse 2001, 2006). But the minimum size of geo-engineering projects is, by definition, on the scale of an entire planet. Small settlements in Venus's atmosphere could allow for geo-engineering projects to be tested on a planet that already experiences an extreme greenhouse effect. The effects of the project could be observed with fewer human lives in jeopardy before implementing it, or deciding against implementing it, on Earth.

Free floating habitats offer incentives to experiment with more environmentally sustainable technologies and practices. Many of the political barriers to such innovation of new technologies and practices would be reduced out of necessity in a settlement with a small and finite resource pool. At the very least, it would be more difficult for interests vested in a more unsustainable status quo to block the development and spread of these technologies and ideas. Furthermore, given the appropriate mechanisms, such innovations may translate to terrestrial use.

Conversely, the small scale of a settlement within an asteroid would force similar innovations for dealing with resource sinks. While a single asteroid likely has more resources than its settlers would need, the limited physical space within it would force its supporters to come up with innovative technologies and practices for dealing with the inevitable waste products from the use of those resources. Much like with free floating habitats, this would provide an opportunity to utilize these innovations (both technical and social) to deal with terrestrial problems.

Of course these benefits are just speculative. One of the major problems with path dependency is that, because alternative pathways are excluded, there is not sufficient opportunity to learn about the potential benefits lost from pathways never tried. In spaceflight, this is true to such a degree that it becomes very difficult to imagine how the, so far expensive and elite, endeavor of outer space development could possibly be of any benefit to those who can't afford to participate. However, it seems unlikely that this will change if private executives exercise disproportionate control over space development, no matter their trajectories. In so far as public goods like reduced consumption and more sustainable living cannot be monetized; there is no incentive for private companies to work toward those goods. Other incentives will have to be provided by pursuing alternatives to privatization itself.

Previously I have suggested that one mechanism for protecting against obduracy, and specifically path dependency, may be to increase the relevant interest groups which are included in decision-making and agenda setting. Pluralism may be a powerful tool in staving off obduracy. But, given this case where adding at least a few new business interest groups was not sufficient, what mechanisms might protect new sets of actors from simply perpetuating old persistent traditions?

First, it may be the case that the increased diversity of interests was simply insufficient. That Mars happens to fit the values of some of the most prominent business leaders in spaceflight does not show any particularly compelling general benefits to the public. That private companies like SpaceX were able to force their way into commercial spaceflight despite the interests of established contractors only proves the power of such new actors, not the openness of spaceflight to new interests. If pathways for more democratic decision-making are desirable, that requires relatively equitable distribution of power between agents (Dahl 1982). Since that is not currently the case, then some sort of mechanism should be put into place that protects minority or underrepresented interests (Woodhouse 2007). For example, the critique that colonizing Mars is akin to leaving those most harmed by the consequences of technological society, such as climate change or colonialism, to their fate is ignored by powerful proponents of spaceflight. Is there a way to proceed with colonization and space development that addresses this concern? Preventing path dependency that guides space development away from this question will require the inclusion of so far excluded interests.

Even simply supporting groups that think about spaceflight in non-economistic terms as such economistic thinking becomes prevalent would help protect against path dependency. SpaceX, Boeing, and other companies which have expressed interest in Martian colonization are all interested in the economic returns the planet has to offer. Just as the patent structure of 19th century America led Finley to focus on bridge designs that were unique, cheap, and simple (Kranakis 1989, 1997), laws and regulations in the United States incentivize participants to be more concerned with profits and costs than safety or social goods broadly conceived. As congress passes new laws for space and new regulations, it will be worth considering whether such laws promote or disable diverse interests and incentives.

Not only has privatization further entrenched the particular pathway of development towards Mars colonization, but the economistic thinking that undergirds this pathway has itself become path dependent. None of the potential pathways for space development are neutral. Each one will have different benefits and costs experienced by different groups. The current pathway towards Mars clearly favors executives of whichever companies can manage to get first-movers advantages. In addition to extremely large profits, if these executives get their way, the massive economic forcing function Musk spoke of will be entirely dependent on a small handful of space development companies and their leaders. Policymakers are already reticent to enact policies which might hurt major companies, even when those policies might provide major benefits for other groups. Consider the subsidies cities are willing to provide to a company as profitable as Amazon for their second headquarters (Garfield 2018). Consider that Warner Brothers was able to strong arm the entire sovereign nation of New Zealand into cutting back labor rights just by threatening to film The Hobbit trilogy elsewhere (Edwards 2017). If a handful of banks were considered “too big to fail,” having a small set of companies that alone control the fate of an entire planet’s population invites severe abuses. Maintaining the viability of alternatives is a necessary part of preventing such undesirable outcomes.

5.6 Conclusion

This chapter has analyzed the path dependence of both Mars and of private spaceflight development. It has shown that privatization has increased its own path dependence as well as the path dependence of a particular vision of Martian exploration. It begins with a historical analysis examining Mars as the dominant trajectory for human spaceflight. This first section, following the explanation of path dependence, establishes that NASA administrators, and later private executives, have pursued the trajectory towards Mars for human spaceflight without much consideration of other potential options. The next section analyzes how privatization has contributed to this path dependence. Proponents of Martian exploration have certainly benefited from increasing privatization, but Mars exploration and privatization are mutually reinforcing. Thus the final section demonstrates how private executives disproportionately benefit from the current trajectory of Mars development. The present privatization of spaceflight not only creates a path dependence towards Mars, but a path dependence of the economistic values that currently drive spaceflight and space development.

This chapter does not show the path dependency of spaceflight in general, but of a particular vision of spaceflight. Therefore, it also shows how the distribution of benefits and expenses is path dependent: the pathways analyzed here all have benefits for some, and expenses for others. Values are becoming path dependent. In the contemporary context, it is a certain set of values that are mutually constitutive with private spaceflight. These economistic values (profits, cost efficient launches, economically productive space development, consumption capacity, and others) are becoming obdurate given the current choices about how spaceflight should be conducted and governed. Those interested in the future of human endeavors in space must ask if these are the values they want steering the future of spaceflight, and if it might be better to be able to shift those values later rather than allowing hasty decisions now to determine the spaceflight of the future.

Not only has this chapter demonstrated the disproportionate benefits for spaceflight executives, it has also shown how it prevents the broader benefits of learning. The benefits of various alternative pathways, such as development of Venus, revolve around improved learning. For example, development of Venus might provide important insights into coping with climate change. Beyond this, prematurely limiting potential future options based on the values of a small set of influential decision makers prevents learning about future improvements. No one can predict all of the future benefits and costs of Mars exploration. It might well be that Mars is a good choice, but it may also be that alternatives could provide more benefits for more people more of the time. If the only way to discover this is to actually try alternatives, then path dependence presents a significant barrier to such learning.

6. Momentum

6.1 Introduction

As time goes on, technological systems can get bigger and more difficult to steer. An early analysis of this phenomenon comes from Hughes's (1969) study of the hydrogenation process in Germany. Before WWI, the German government and chemical industry executives invested substantially in industrial processes for the artificial production of nitrogen fertilizer. But markets would not bear the increased production capacity after WWI. However, scientists and engineers trained in this process, facilities built to conduct the process, industries and companies constructed around the supply and distribution of artificial nitrates, and substantial government investment created barriers to down-sizing the industry. Thus executives had considerable incentives to modify the process, facilities, and personnel to produce artificial substitutes for petroleum products. Initially, this seemed to executives of companies such as I.G. Farben like a viable peacetime industry that would simultaneously help usher Germany into the future, as they lagged behind in the automobile revolution (Hughes 1969). When the prospect of increased demand from the military development of Germany under the Nazi party arose, I.G. Farben had but to continue doing what they were already doing to take advantage. Whether the industry leaders involved actually supported Nazi ideology was thus largely irrelevant to the decision to support the Nazi war effort. Rather than deconstruct or sell the facilities, liquidating the capital investments, or exploring other potential uses for the process via research, this so called momentum substantially steered the considerations of executives and thus the adoption of such alternative options, contributing to obduracy and erecting a barrier to *social* steering of the use of the technology. Momentum, therefore, is a different mechanism by which obduracy is created than covered by the other chapters. Building momentum in one direction means that other options are foreclosed. Increasingly large sets of people gain increasingly large and diverse investments in the status quo, making the selection of alternatives less likely as momentum increases.

This chapter analyzes how the governance of spaceflight via market values, along with the privileging of business interest, potentially make spaceflight programs more difficult to alter in response to future needs through technological momentum. How have private spaceflight companies responded to longstanding design and organizational problems which have been barriers to routine spaceflight in the past? What influence have the decisions of these business leaders had on the direction of space policy and the more traditional contractors? How exactly have these influences acted as potential catalysts or causes of increasing technological momentum of private spaceflight?

The following vignettes will address aspects of technological momentum as seen in the privatization of spaceflight. This chapter seeks to analyze the barriers momentum raises to reconstructing space development. By examining the pace of innovation, and the growing influence of the technological system of private spaceflight, I will identify where and how momentum is increasing.

6.2 Characterizing Momentum

Technological momentum is a concept akin to its namesake from physics, which offers an alternative explanation for seemingly autonomous technological systems. In physics, momentum is described as the mass of an object multiplied by its velocity (which describes both speed and direction). Thus all objects with non-zero velocities have momentum. It is very difficult to change the speed and direction of objects with very high momentum compared to those objects whose momentum is relatively low. An object can have high momentum by either being very massive, having a high speed, or both. Likewise, technological systems have mass. This mass consists of both technical and organizational components: fixed capital in the form of machines, factories, and transportation systems, but also various groups of people committed to that system, such as engineers who sustain it in order to avoid deskilling within their discipline (Hughes 1987a, 76–77). Technological systems also have speed. The pace of innovation or the rate at which new components are brought into that system constitute the "speed" of the system, so a fast pace means a system has more momentum (Hughes 1987a, 76). Finally, technological systems also have direction in the form of organizational goals (Hughes 1987a, 76). As time goes on and the mass of a system grows, it gains more momentum (Hughes 1994, 107).

Momentum often increases because of the desire to use excess capacity or minimize perceived inefficiencies, referred to by Hughes as "reverse salients" (Hughes 1987a, 1994). Hughes utilizes the example of an electric utility. Consumers use more electricity at peak times than at other times, and consumer preference pushes utilities to have the capacity to supply that electricity. But all of the times the demand is low, that capacity goes unused (Hughes 1987a, 72). To make up for this, there are two strategies that managers in the system may employ. First, they can diversify the demand. If a utility can find customers whose peak demand differs from existing customers, they can reduce the unused capacity without having to increase maximum capacity. Alternatively, they can diversify the business to make up for losses from inefficiency in any one sector. A utility could control the coal mines that supply their coal or the manufacturers who make their equipment, two sectors which profit from increasing generation capacity whether that capacity is used or not (Hughes 1987a, 1994). Both strategies require increasing the number of components within the system, such as adding new customers or new industries. This increasing interdependence between these new components and the technological system increases momentum.

If reverse salients are the relative inefficiencies of some parts of a technological system compared to others, then the way in which decision-makers respond to reverse salients is what creates momentum. Unused generation capacity is an example of a reverse salient. A reverse salient is simply any component, human, technological, or organizational, that a manager must change if she wants to increase the efficiency or productivity of the technological system (Hughes 1987a, 73–75, 1994, 102–3). Reverse salients are problems solved within the system. Innovations address reverse salients if they enable more efficient use of the current system, but are revolutionary if they seek solutions through alternatives to the system. Consider the case of the development of AC power. Edison's DC power system had the problem that power transmission was limited by distance. Edison attempted to solve the reverse salient of transmission distance for DC power through several unsuccessful innovations. Instead, AC power presented an alternative to Edison's power infrastructure for which transmission distance wasn't a problem (Hughes 1983). Edison's innovations addressed the reverse salients of DC power, while AC power was a revolutionary alternative. In addition to promoting growth and thus increasing the mass of the system, addressing reverse salients also increase the speed of innovation. Because reverse salients can be a starting point for innovations that increase the number of components in a system, they are a clear sign of potentially increasing momentum.

As managers address the inefficiencies of reverse salients, they create momentum. Hommels (2008, 338–39) describes how solving reverse salients creates long-term cultural context that supports the system. At first, investors may support a system through the addition of labor, factories, and the development of natural resources. As the system grows, experts may be trained to operate its components. New laws will pass to incorporate its operation into the legal system, an increasing number of organizations will participate. As time goes on, these dimensions operate in tandem so that solving the problems within the system become a sort of cultural tradition, persistent and enduring. Momentum builds along many different dimensions: technical (new technical artifacts), legal (new supportive laws), expert (the addition of experts trained for the system and the educational apparatus which trains them), infrastructural (the factories, transportation networks, and supply chains that support the system), and organizational (the inclusion of interdependent networks of organizations operating within the system).

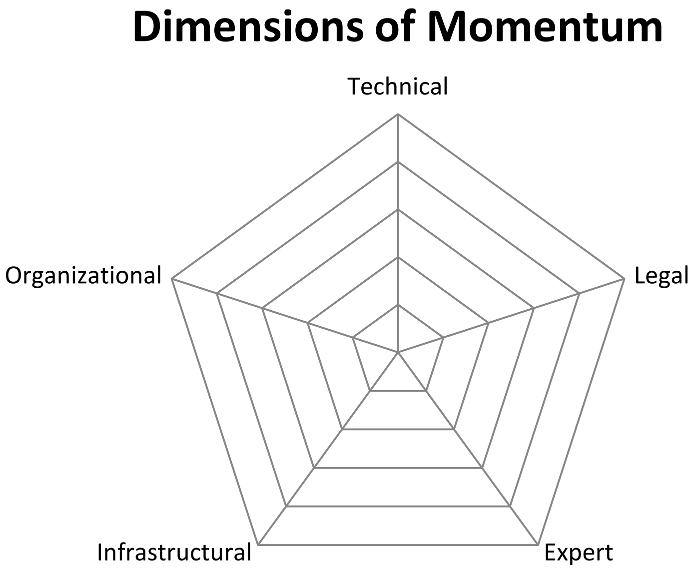

Figure 6.1: Visual illustration of the dimensions of momentum

Each of these dimensions is visible in the example of Edison and the DC power system. Generators, batteries, arc lamps and a myriad of other technological artifacts enabled the generation, distribution, and use of electricity via his DC power system.

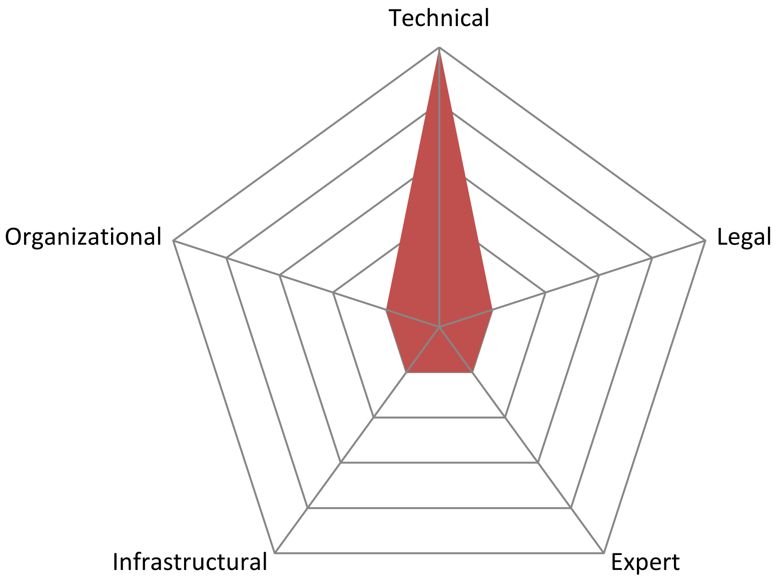

Figure 6.2: Visual illustration of technical momentum relative to other dimensions of momentum

Educational institutions trained electrical engineers and other professionals, who passed on this information via professional journals, training whole fields to think in terms of DC power problems even if not directly employed by General Electric.

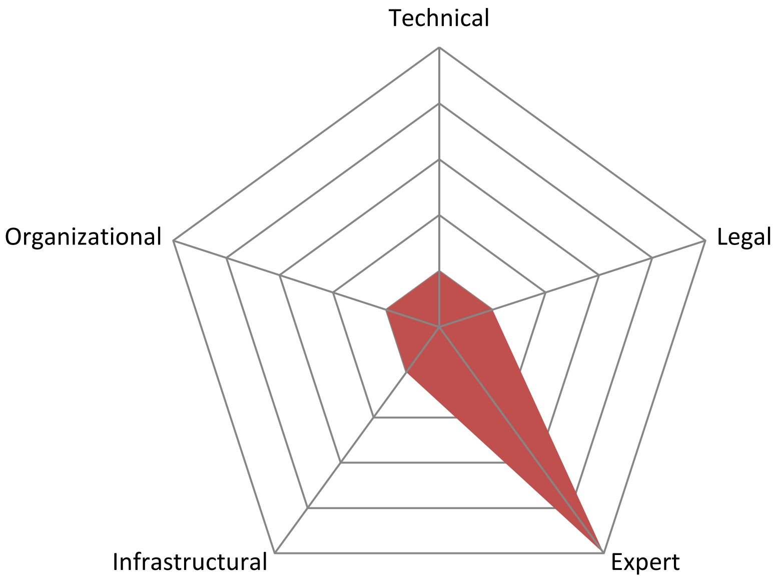

Figure 6.3: Visual illustration of expert momentum relative to other dimensions of momentum

Regulations on the new industry favored DC power generation, such as street lighting mandates in cities. Edison actively lobbied to pass laws which would hinder the development of AC power (Hughes 1983, 108).

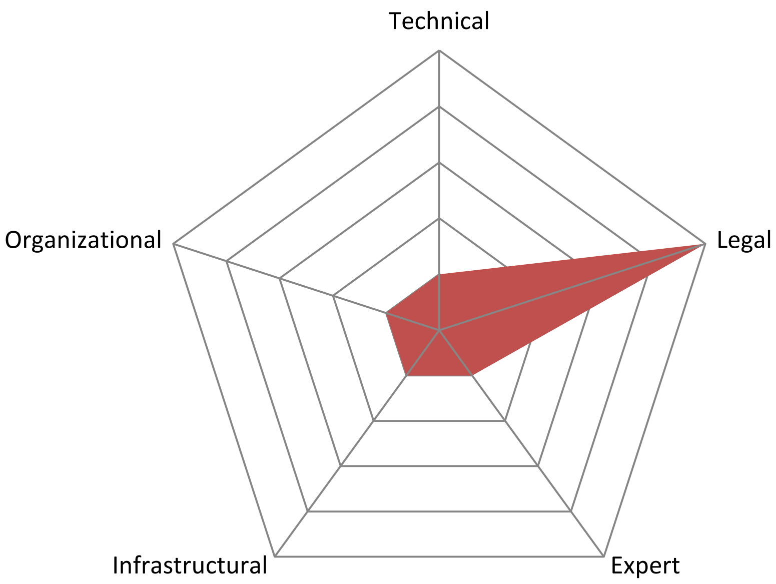

Figure 6.4: Visual illustration of legal momentum relative to other dimensions of momentum

New organizations sprang up to profit by embedding themselves in the system. Inventors made new generators, DC motors, and more for DC power systems. Construction companies installed new power stations and transmission lines. Manufacturing firms specialized in producing the equipment necessary for DC power (Hughes 1983, 18–106).

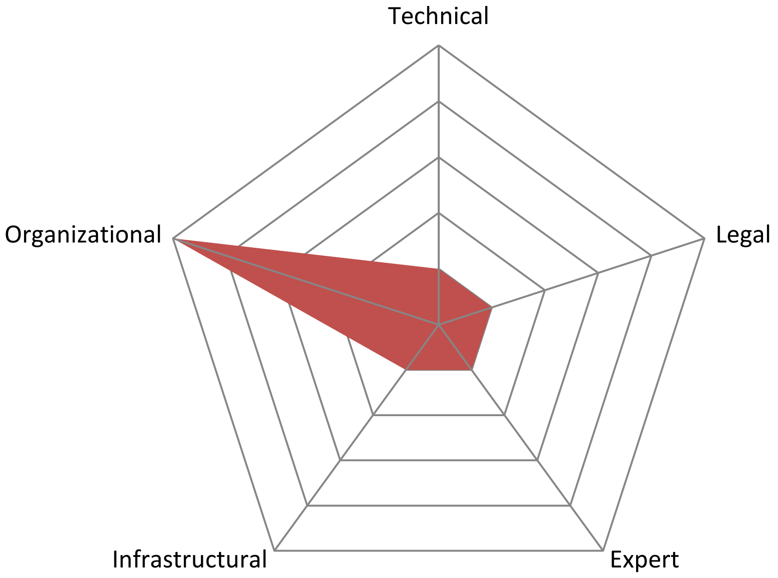

Figure 6.5: Visual illustration of organizational momentum relative to other dimensions of momentum

All of these dimensions combine such that it became very difficult to dislodge the system of DC power. So much so that, even though AC power became the dominant system after the failure to solve the infrastructural reverse salient of transmission distance, it was still General Electric (even without Edison at the helm) that eventually forced and profited from the switch to AC power systems.

A common interpretation of technological momentum within STS is that it serves as a middle ground between social construction and technological determinism (D. G. Johnson and Wetmore 2009). This interpretation treats momentum as if it were providing a mechanism by which technology may exert influence of the social world. If technology has momentum, then it determines social factors rather than vice versa. But does technological momentum dichotomize between social and technical realms in the same way as these descriptions?

Hughes argues that technological systems have momentum, not necessarily technological artifacts themselves. In a technological system, the components are viewed symmetrically.

Technological artifacts, human beings, organizations, social values, and others are all components and all interact systemically (Hughes 1994, 102) without substantively differentiating between "technological" or "social" components. Technological systems are not purely technological. The environment, Hughes's term for those things not part of the technological system under analysis, is also not purely social. This too consists of technical, human, and social components (Hughes 1994, 105). So to say that technologies become deterministic as time goes on is to oversimplify Hughes's conception of systems. Technological systems become more determinant of their environments over time, but both system and environment consist of parts that are technical, human, and social. Therefore, rather than use technological momentum as a position on a spectrum between social construction and technological determinism, I find it useful for this analysis to place added emphasis on the concept of technological systems and thereby avoid this dichotomy altogether.

Using this frame of analysis, increasing momentum of private spaceflight does not mean technological determinism of spaceflight, but a greater influence of privatization over the five dimensions of momentum which I have identified: technical, legal, expert, infrastructural, and organizational. If momentum increases along these dimensions, this in turn means that it will be increasingly difficult to steer away from privatization even when such steering seems potentially desirable. As Hommels points out in her analysis of the momentum of the city, the mass of components in a system with momentum means a large number of actors with a great deal of investment in maintaining the system (Hommels 2008, 337–38). This alone would prevent other groups who might want to make beneficial changes by pursuing their alternatives. Worse yet, however, this momentum can "transcend local contexts," embedding itself into culturally shared values (Hommels 2008, 341) and becoming virtually impossible to dislodge, no matter the potential benefits of doing so. It means more aspects of spaceflight becoming privatized, private spaceflight executives having a greater influence over the related organizations, laws, policies, and decision makers, and that privatization increases the pace of innovations which add components to the spaceflight system rather than alternatives. Does private spaceflight currently exhibit any of these increases in momentum?

6.3 Identifying Reverse Salients

Remembering Hughes's analysis of technological momentum, reverse salients are subsystems that have lagged in their performance or are otherwise identified as barriers to the performance of the technological system. In the case of the development of the American electrical grid, a substantial reverse salient of Edison's direct-current (DC) system was a low transmission distance. Edison attempted to solve this problem by changing from a two-wire transmission system to a three-wire one, trialing different generator configurations, and even adding batteries to the distribution network (Hughes 1983). These innovations were conservative, as they solved the reverse salient by increasing the size of Edison's DC power system; each new component required new supply chains, new engineers, and spending on maintenance along with other connected additions that increase the costs of deconstructing the DC power system in favor of an alternative. Eventually, however, alternating-current (AC) overcame the problem, but did so by presenting an alternative to DC power altogether rather than alter the existing DC system in some way, and was thus a revolutionary innovation (Hughes 1983). Reverse salients are an important catalyst in momentum building. As the standing inefficiencies in a system, the desire to solve reverse salients provides the initial impetus for new investment and innovation in the system. The different ways these inventors address reverse salients advantage different people, and can serve to either entrench or challenge those who are deeply committed to the status quo of that system. What are the standing inefficiencies of spaceflight?

Starting with pre-Apollo RLV programs and going through the X-33 and 34 programs that ended at the turn of the millennium provides a useful basis for performing a similar analysis of reverse salients in spaceflight. By discussing the reverse salients originally identified by NASA, and analyzing how NASA attempted to address them, this chapter is performing a parallel analysis to Hughes's analysis of Edison's DC power system. NASA's problems with reusability are like Edison's problem with the transmission distance of DC power. Their attempts to address them are like Edison's many failed innovations to extend that transmission distance. Is private spaceflight, then, like AC power? Offering alternative solutions to longstanding reverse salients and challenging the status quo? Or are they simply building on these already established technological paradigms to entrench their own positions?

The lack of launch vehicle reusability was identified early on as a major reverse salient in spaceflight. Operating disposable launch vehicles in stages was seen as wasteful of budget, manufacturing capacity, fuel, and the launch capacity of rocket engines. Both the North American X-15 hypersonic space plane and the Boeing X-20 DynaSoar experimented with reusability to solve such perceived wastefulness from 1956 to 1968 (Jenkins 2000).

The X-15 was designed to focus on propulsion and stability, both of which were barriers to achieving reusability. The reason launch vehicles operated in disposable stages was because the weight of fuel and the size of the engine increase exponentially relative to one another. For a single reusable stage to get to orbit, the size of the engine necessary to lift the weight of its own fuel was unfeasibly large. Designers needed an engine that could operate in and out of atmosphere and could provide the necessary propulsion without disposable stages but didn't weigh down the vehicle. A reusable vehicle would also have to land, rather than parachute into the ocean, so controlled return of the vehicle required stability both at hypersonic and subsonic speeds, which proved difficult. It also required advances in materials which could withstand the heat of reentry and the forces of high-speed maneuvers. The X-15 was an initial effort at finding solutions to the inefficiencies of disposable launch vehicles.

Operating in tandem with the X-15, and for the same general purpose, the X-20 was designed as a hypersonic near space vehicle focusing on the problem of gaining lift at hypersonic speeds (Wade 2016a). Designers hoped the launch vehicle could use lift to provide some of the upward force while in the atmosphere to allow for less powerful engines which would use less fuel. With this focus, the X-20 was designed to solve many of the same problems as the X-15. Although some of the specific design problems would change, these two programs set the stage for reusability to be the primary, general design challenge for human spaceflight even to today.

Much like Edison’s innovations to improve the transmission distance for DC power, the innovations from the X-15 and X-20 had not panned out even decades later. Although NASA had the space shuttle, it had not brought the cost savings and other benefits proponents of reusability had predicted. The development costs were massive, the shuttle was not fully reusable, and it did not launch frequently enough to benefit from having even partial reusability. While NASA had accomplished some degree of reusability, the technology was incomplete and did not solve the inefficiencies it was intended to solve. So, in the 1990’s and early 2000s, NASA conducted extensive development of new reusable vehicles. Although none of those vehicles became operational they, again, demonstrate standing inefficiencies in spaceflight. Dominant actors do not usually support revolutionary innovations which tend to decrease their control rather than increase it (Hughes 1987a). If NASA is considered a dominant actor during these reusability development programs, then the innovations prioritized in these programs are likely to be conservative. They can then be used to make a comparison to those innovations being pursued by private space development companies today. What were the innovations NASA focused on to solve reverse salients? Have private spaceflight companies continued to focus on these innovations, trying to get them to work, or have they attempted to pursue alternatives?

One of the earliest experimental designs from this era was the Delta Clipper Experimental (DC-X), which was designed to demonstrate technologies which could improve the turnaround time for re-launching a reusable launch vehicle. Such new technologies would allow NASA to address the reverse salient that the space shuttle launched too infrequently to take advantage of reusability. The program began in 1991 with the first test flight in 1993, when it demonstrated vertical takeoff and landing techniques. The idea was that a launch vehicle that could return and land vertically on the same pad from which it launched could be refurbished quickly and turned around for re-launch. The DC-X program tested two other innovations to achieve this goal of fast turnaround reusability. A highly automated control center requiring only three operators expedited the launch process itself and engines capable of throttling back to 30% of full lift enabled vertical landing (Balistic Missile Defense Organization 1996). The history of the DC-X shows the importance of vertical takeoff and landing as conservative innovations for reusability. Specifically, automation and variable throttle engines may be considered conservative innovations for this purpose.

Another early experimental reusable launch vehicle was the National Aerospace Plane (X-30), which was designed to address the reverse salient of staging to move from the partial reusability of the shuttle, to full reusability. Much like with its disposable predecessors, engineers designed the shuttle to operate in stages. Started in 1990, the X-30 was designed to demonstrate technologies necessary for a fully reusable single-stage to orbit (SSTO) space plane (Aeronautics and Space Engineering Board 2012, 97). The first step, much like the X-15, was balancing weight and thrust. The X-30 supplemented smaller rockets with a scram-jet engine. Because scramjets don't require liquid oxygen, they can reduce the fuel weight without multiple stages (Aeronautics and Space Engineering Board 2012, 97). The X-30 project identified six other technologies to solve problems around reusable SSTO vehicles: composite material for the hydrogen fuel tank (to reduce weight), a propellant utilization fraction of 0.74 (a measure of the fuel efficiency of the vehicle), carbon fiber aerodynamic surfaces, high temperature aerodynamic materials, computational models for scramjet engines, and slush hydrogen as fuel (which is more dense than liquid hydrogen thus reducing the size and weight of the vehicle) (Wade 2016b). The X-30 project focused on propulsion-related innovations to solve the problem of reducing costs through weight reduction and reusability. The X-30 was cancelled in 1993 and left behind specific reusability challenges that can help identify contemporary innovations.

Like the X-30, the X-33 was a demonstration platform for technologies that would support reusable SSTO. NASA contracted Lockheed Martin to test new materials and propulsion technologies necessary for SSTO reusability (Launius 2004b; Aeronautics and Space Engineering Board 2012). Specifically, the X-33 was to test the new Rocketdyne XRS-2200 liquid hydrogen engine to demonstrate the possibility of achieving at least a 0.88 mass fraction, the ratio between the vehicle's pre-launch and orbital weights. Since most of this mass comes from fuel, NASA's goal was to reduce fuel consumption thus addressing one of the major reasons why the shuttle was only partially reusable. To further reduce the vehicle weight, it was also intended to test new copper alloy composite materials for the fuel tanks (Aeronautics and Space Engineering Board 2012, 98).

NASA also used the X-33 to test new organizational innovations. The X-33 was meant to eventually become an operational vehicle that Lockheed could use to sell launch services to NASA rather than be a direct replacement for the space shuttle. But Lockheed was also involved in the military's Evolved Expendable Launch Vehicle (EELV) program and if Lockheed developed a SSTO vehicle, they would be splitting the market with their own expendable vehicle thus reducing the cost savings from reusability. Lockheed executives were not as invested in SSTO as NASA administrators (Bromberg 1999a). After a failure of the composite fuel tank during testing, the project was cancelled in 2001 after only being 40% complete but costing over $1.5 billion. The X-33 project attempted to innovate new engines, materials, and relationships with the private sector in order to address the reverse salients which hindered the development of a fully reusable launch vehicle. But by the end of the program, they had not succeeded.

The X-34 was a technology demonstrator focused on the price per launch as a reverse salient. High costs were perceived as being one of the causes for schedule slippage of space shuttle launches, as well as a barrier to more private industry involvement. So, the first goal of the X-34 was to reduce the cost of launching to orbit from $10,000/lb, the price of the shuttle, to $1,000/lb (Amatore and Humphrey 1999). These same price measurements are still the standard scale for private spaceflight. The second goal was to demonstrate a new organizational model where NASA funded the private development of a vehicle that NASA would later purchase as a service, similar to the contemporary Commercial Orbital Transportation Services (COTS) program. Engineers utilized technical innovations such as thermal protection, cheaper propulsion, and faster turnaround times for refurbishment to reduce the costs of launches. For example, the X-34's Fastrac engine used kerosene fuel rather than innovate a new fuel system, but took advantage of this legacy technology to develop a new engine that had substantially fewer parts so was cheaper to manufacture and faster to refurbish (Amatore and Humphrey 1999). NASA managers had hoped that the innovation of partial privatization would be self reinforcing with the goal of reduced launch costs, but Orbital was unable to meet their financial obligations to the program so rather than increase NASA funding, it was cancelled in 2001.

Individual facets of obduracy do not necessarily act in isolation. Recall the discussion from Chapter 3 about NASA's RLV programs contributing to the accumulation towards greater authority of private executives and greater influence of values associated with privatization. This accumulation lays the foundation for the creation of momentum. First, the failure of these programs to develop a successor to the space shuttle and second, the cost splitting techniques that were further developed into contemporary funded Space Act Agreements (SAAs). Developing a launch vehicle replacement should happen before the launch vehicle needs to be replaced. But because these RLV programs failed, NASA didn't start developing the shuttle's replacement until the Constellation program, which simultaneously included the shuttle's retirement. The steady accumulation towards privatization started creating momentum for privatization early on. This momentum was a substantial barrier to the Constellation program's renewed focus on a public program. Without a foundation of NASA-based alternatives to build on it is no wonder that NASA wasn't able to complete the Constellation program and the needs of industry executives outweighed the needs of NASA proponents. NASA was developing highly reliable human transports, not launch vehicles designed to minimize costs and compete in the market. It should therefore be little surprise that these partnerships didn't pan out as intended. How could

NASA have run these programs so that they had a greater likelihood of success? What alternative strategies to private partnerships could have alleviated budget stresses?

One of the major barriers to the success of these RLV development programs was a lack of policy goal (Pace 2016). If one imagines technological development through the metaphor of momentum, it might look something like attempting to move a large boulder around. Some locations are better than others, so as the boulder starts rolling, it is important to have some idea of what the criteria for desirable endpoints are. From there, some attempt to steer the boulder is clearly preferable to allowing it to roll where it will. Any object, moving or not, will have momentum, so moving slowly and making small changes with a goal in mind is the most likely strategy to end as close as possible to the desired location. Moving quickly and only making adjustments in response to immediate problems leaves the destination almost in the hands of fate.

Thus the first major challenge to reducing momentum is to set out with some kind of goal. Having such a goal makes contending with momentum easier. Edison's DC system began with a relatively simply goal of transforming an energy supply into electricity that meets demand as efficiently as possible (Hughes 1983, 5). Thus, it easy for Edison to identify and solve reverse salients. RLV development had been working towards potentially contradictory goals: replace the space shuttle, develop new technologies, and support increasing privatization. Without clear goals, the result was selected based off of accumulation and momentum in favor of those actors who could marshal such phenomena to their advantage.

If starting with clearly defined and preferably democratically deliberated policy goals helps control technological development even as momentum begins to set in, what strategies might help to reduce it? Again, thinking in terms of the physical analogy of momentum is very useful. If momentum is mass times velocity, momentum can be protected against by protecting against increases in speed. From a technological standpoint, this might look like development through gradual scale-up. Woodhouse (2005) describes how green chemical researchers have incorporated strategies such as starting with small quantities of chemicals, extensive testing, gradual scale-up on testing and production if results are favorable, and generally learning by doing. These researchers are beginning to see such strategies as equally important to the chemical compounds themselves for achieving the goal for chemistry of “benign by design.” If NASA would like the development of outer space to be equally as benign, administrators should consider the benefits of strategies such as gradual scale up and not just focus on new technologies and reducing costs through privatization.

What difference might such a strategy have had on the RLV development projects discussed in this section? One potential issue NASA officials faced, especially with the programs conducted at the turn of the millennium, was that the scale of the projects started too large. The X-33 and 34, for example, cost $1.5 billion and $112 million respectively by the time they were cancelled. Such investment of resources, as well as pressure from private partners, locked NASA administrators in to the goal of developing reusable full scale launch vehicles. Program officials were thus unable to respond to testing by cancelling only those aspects of the programs that were least promising, and gradually scaling up the most promising aspects. Starting at smaller scales and then scaling up projects as they showed success could have allowed NASA to keep costs down until they had selected a single development project to fully implement.

The examples used in this chapter are meant to show some of the most important reverse salients in spaceflight. NASA spent a great deal of time and resources on reusability as a solution. This may have been right-headed or not, but ultimately NASA was unsuccessful at solving the inefficiencies they set out to solve. Thus, these same problems are left for contemporary private companies to address. Will they create revolutionary alternatives, or will they address these reverse salients utilizing the same ideas originally attempted by NASA? Different ways of addressing these reverse salients in spaceflight advantage different paradigms or visions of spaceflight. What paradigms gain advantage through the innovations of private spaceflight companies?

6.4 Innovation and Increasing Momentum

If the NASA experimental programs discussed are like Edison trying and failing to solve the reverse salient of transmission distance, private spaceflight executives would spread the belief that they are developing AC power: a revolutionary alternative. But is this the case? Private spaceflight companies have maintained a rapid pace of innovation, but are they as revolutionary as AC power was to DC power, or are private companies building within the same technological paradigm established by NASA in order to support their preferred outcomes while foreclosing others? By comparing those private innovations to NASA's RLV programs using the five dimensions of momentum established at the beginning of the chapter, this section analyzes what changes are actually being made to spaceflight through privatization. What reverse salients are private spaceflight companies responding to with their innovations? How are these innovations implemented? Who participates? Is this akin to the switch to AC, with the invention of the transformer and a relatively sudden challenge to DC power, or a gradual change through accumulation that ends up very large, entrenching the values of those seeking to build momentum?

6.4.1 Technical Momentum: New Technologies and Techniques

In NASA's bid to achieve full reusability and overcome the reverse salients they identified in spaceflight, innovations to engines and fuel were among their key strategies. This strategy remains relevant, as some major innovations coming from private companies entering the spaceflight industry have been increases to fuel efficiency and engine system power. In some cases, the problems being solved and the innovations being proposed have a direct lineage back to these NASA programs. At the very least, however, none of the new engines or fuel systems seem to diverge either from one another or from the original strategy unsuccessfully pursued by NASA.

SpaceX has developed their Merlin 1-D engine with improvements in fuel efficiency, using the same strategy as the Fastrac engine from the X-34 program.. Although the 1-D uses kerosene fuel and can only achieve 934 kN of thrust (Space Exploration Technologies 2012a) (less than half of what the space shuttle main engine could produce at 2200 kN), the Merlin 1-D engine has the highest thrust-to-weight ratio of any engine ever operated, at a 190 thurst-to-weight ratio compared to 54 for the shuttle's RS-25 (Aerojet Rocketdyne 2017b). In other words, SpaceX executives and engineers have followed the same strategy used in the Fastrac engine: utilizing a well understood fuel process to create a simple and efficient engine with limited total thrust but which uses very little fuel, leaving more weight for payloads.

The 1-D also resembles the Fastrac through a focus on minimizing production costs for the engine. Launching a Falcon 9 with ten Merlin engines costs $62 million. Assuming the engines account for 65% of the total cost, a single Merlin would come in at $4 million (Space Exploration Technologies 2012c). To show context, an estimate for the cost of restarting RS-25 production (the space shuttle main engine) to make six new engines totals $1.5 billion. Even only accounting for the production costs, rather than the other costs associated with the restart, it would take $350 million to manufacture those six engines, meaning $58 million per engine

(Bergin 2016). The innovation of the Merlin engine addresses efficiency, engine weight, and production cost, the same problems NASA tried to solve with the X-34's fastrac engine.

SpaceX's larger engine series, the Raptor, borrows NASA's innovations to fuel while still attempting to address the same reverse salient of thrust-to-weight as the 1-D, while delivering a much higher thrust. Although only in the testing stage, the Raptor is expected to achieve over 3000 kN of thrust (Belluscio 2016) using cryogenic methane as the fuel rather than kerosene or liquid hydrogen. The X-30 originally attempted to use cryogenic methods to partially freeze hydrogen fuel to slush, and SpaceX uses a similar method for Methane. While no fuel combusts as efficiently as liquid hydrogen SpaceX designers accepted this setback, focusing instead on the advantage that cryogenic methane is far cheaper and still delivers high thrusts with low flow rates. A small alteration in the original innovation proved sufficient to meet at least the goal of lighter fuel originally set by the X-30 program. Thus the Raptor engine addresses the problem of balancing cheap fuel with high thrust and, more importantly, gaining a high thrust to weight ratio by reducing the fuel's flow rate. These are the same techniques pioneered by and problems identified through the X-30.

Blue Origin, too, has been using NASA innovations to solve these reverse salients. It's "Blue Engine" series includes the BE-3, which uses liquid hydrogen to produce up to 490 kN of thrust. This is not substantial thrust compared to other engines, but it is capable of throttling down to as low as 110 kN of thrust, making it particularly useful for controlled vertical landings (Blue Origin 2017) and meeting the criteria from the cancelled DC-X. The BE-4, now in development, will use liquid methane like the SpaceX Raptor, but will produce 2400 kN of thrust. Assessing the BE-4 relative to the comparable AR-1, being developed by Aerojet Rocketdyne, shows the focus on innovation for the BE-4. The AR-1 produces 2200 kN of thrust, slightly less than the BE-4, but the BE-4 is 40% less expensive (Griffin Communications Group 2014; Aerojet Rocketdyne 2017a). The emphasis on cost reduction through simplification of design is similar to the X-34 program. The emphasis on vertical takeoff and landing comes from the DC-X program almost directly. Blue Origin even hired engineers from the DC-X project (Schwartz 2007).

Once Edison initiated his DC power system, it grew because other engineers and companies added new artifacts designed to solve the reverse salients of the system. In much the same way, these private companies are making their own goals for spaceflight more resilient by solving the reverse salients NASA originally attempted to address. So, while private spaceflight entrepreneurs are making all sorts of new innovations to engines, they are not really doing anything new. They are using innovations pioneered by NASA to make spaceflight cheaper, more economical, and more profitable. Just like the myriad of innovations which cemented DC power as the dominant form of electrical generation and distribution for some time, private space development companies are cementing their interests by building on the innovations of NASA programs.

Engine and fuel innovations are not the only ways in which private spaceflight companies are enlisting an increasing number of technological artifacts into their system. Blue Origin engineers have designed both their New Shepard suborbital launch vehicle and their New Glenn orbital launch vehicle to return to the launch pad after use, touching down via a controlled vertical landing using the vehicles rocket engines (Blue Origin 2017). SpaceX uses the more technically challenging technique of controlled vertical landing on a platform built atop a floating barge. While the unstable barge makes this task daunting, the barge can be relocated to accommodate more fuel efficient reentry trajectories for the launch vehicle (Space Exploration Technologies 2016).

Other companies, such as ULA and Arianespace, are opting to have their engineers continue a strategy of partial reusability adopted for the shuttle, and to address the shuttle's reverse salients using other innovations. Analysts in both companies have determined full reusability to not be economically feasible, as the estimated cost of re-manufacturing much of the launch vehicle first stage is less than that estimated for retrieval and refurbishment (Bruno 2015). Recovery and refurbishment is to be based on the expense of the components, with only the most expensive portions of the launch vehicle, in particular the engines, being reused. United Launch alliance will use an aerial recovery system: the engines will separate from the rest of the first stage, reentering the atmosphere and deploying a parachute. As the engines descend they are to be intercepted by a helicopter which carries the engines to a barge for transport back for refurbishment (United Launch Alliance 2015). Arianespace has an equally elegant and technically complex plan for reusing the engines: the engines will be part of a winged module that will separate from the rest of the first stage and fly as a drone back to be refurbished after it reenters the atmosphere (Benoit 2015). In order to complete their plan, ULA, will have to develop new staging technologies to detach the engines separately from the rest of the launch vehicle, a "hypercone" to simultaneously protect the engine from heat in reentry and slow it down to subsonic speeds, and finally a special parachute system for mid-air pickup by helicopter. Arianespace will also have to develop new stage separation technologies, new reentry techniques, deployable wings, and autopilot technologies to achieve their plan of partial reusability.

These new systems for reusability, or even partial reusability, require a myriad of new pieces of hardware and software and new ways to use them. Edison’s engineers did the same thing, building a whole system of technical artifacts working together in complex and tightly coupled systems. They improved the efficiency of generators and magnetic fields, improved the heat sinks of armatures, created dampening sparking brushes, and improved the efficiency of energy transfer between the magnetic field and the electric motor armature (Hughes 1983, 81). In the same fashion, engineers for SpaceX, Blue Origin, ULA, and Arianespace improve on partial thrust engines, invent stabilizing fins, program software to automatically adjust stabilizing thrusters, coordinate between interdependent systems, invent robust foldable wings, and otherwise create a wide variety of technologies and techniques specifically for executives to improve the cost efficiency of sending their vehicles to space.

Private companies may be innovating, but those innovations fail to create any diversity of potential solutions to the reverse salients of spaceflight. Instead, they simply add components to the technical dimension of momentum. The innovations on engines and fuel map well onto those attempted in the NASA experimental programs. The reverse salients being addressed are the same, and the innovations being utilized are clearly based on those originally attempted by NASA. Each new engine or fuel process adds a technical component to the momentum of private spaceflight.

6.4.2 Organizational Momentum: Getting on the Bandwagon

In addition to a large mass of technological artifacts, the interests of private spaceflight companies are also supported by a large mass of organizations. First there are many different companies performing a myriad of services, but all in service to the privatization of space development. Second, there are organizations that provide support to these companies. Not only does this mean that the there are many organizations with members invested in the values of private spaceflight, like competition and low costs, at the expense of other potential values, but that these organizations actively work to increase the scope of investment in this model rather than others.

Beginning in 1999, a boom in aerospace companies increased the number of competitive companies operating privately in the field of spaceflight. Even including only the most well known and active of such companies, the list includes Bigelow Aerospace, XCOR Aerospace, Blue Origin, Exos Aerospace[11], Virgin Galactic, Space Exploration Technologies, Planetary Resources, Deep Space Industries, among others. Several organizations operate in support of these so called NewSpace companies as well. Astronauts for Hire (A4H) is an organization which provides training for commercial astronauts so that human missions may be conducted without the need for federally employed astronauts. The organization has become a 501c3 not for profit, meaning that the federal government subsidizes this private astronaut training through tax relief ("About Astronauts for Hire" 2010). Thus, A4H provides a tax free service which in many other sectors private companies would be expected to undertake themselves.

Professional organizations also operate in support of private spaceflight companies. The Commercial Spaceflight Federation is a trade organization founded in 2005 that represents the interests of these companies in Washington D.C. ("About the Commercial Spaceflight Federation" 2016). The Space Frontier Foundation is another non-profit advocacy group for NewSpace ("About the Foundation" 2017). Both organizations serve as lobbying and advocacy groups to ensure that the influence of private spaceflight executives extends to groups which would otherwise not be invested in the private model of spaceflight. A large number of

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[11] Formerly Armadillo Aerospace.

companies and other organizations both directly involved in private spaceflight and operating as part of a supporting infrastructure have arisen relatively recently.

Additionally, traditional aerospace contractors have been increasingly responsive to market ideals and more thoroughly incorporating economic motivations at the exclusion of alternatives. As discussed in the chapter analyzing lock-in, several companies are altering their market strategies, their organizational structures, their goals, and even their technological designs in direct response to companies like SpaceX. ULA announced the development of their new launch vehicle, the Vulcan, in 2014 (Bruno 2015), motivated by a change in focus from military launches to economic competitiveness. The change was partially motivated by the momentum of other private companies that pioneered this orientation within spaceflight. SpaceX enlisted the federal judiciary into the system by filing a suit in response to a block buy contract between the Air Force and ULA. The Air Force had purchased several launch vehicles from ULA through an ostensibly competitive process, but Air Force requirements actually excluded any other company from competing. As a result of the suit, ULA's position was weakened. Executives had little choice but to respond to the competition moving away from military aerospace. ULA's design for the Vulcan is also based around the use of the Blue Origin BE-4 engine (Foust 2016) in order to take advantage of their innovations thus strengthening their association with this new wave of private spaceflight companies. Moreover, ULA is attempting to utilize the same sorts of vertical integration and centralized management techniques used by SpaceX and others (Anonymous 2015), thus elucidating the influence such companies have had.

Beyond ULA, the largest space launch provider in the United States, the influence of competition has spread to other companies, including those operating internationally. The Japanese company Mitsubishi Heavy Industries (MHI) utilizes highly specialized designs serving

Japanese government payloads rather than competing for launches with other companies. To the contrary, however, the design of their new launch vehicle, the H3 is meant to compete in the international market through a focus on lowering costs (Kallender-Umezu 2013). Meanwhile, the ESA member states have authorized Arianespace, which once controlled 50% of the global launch market, to develop a new launch vehicle, the Ariane 6, to reduce costs and increase their competitiveness specifically with SpaceX (Cabirol 2014; de Selding 2014). Boeing, although not a launch provider, has partnered with Bigelow Aerospace in the production of their CST-100 capsule for the CCDev program (Thompson 2012; "Crew Transport" 2016). Additionally, after Musk's announcement that SpaceX is developing an Interplanetary Transport System (ITS) to send the first people to Mars, Boeing's CEO announced that they would beat SpaceX to Mars (Muilenburg 2016), showing how Boeings long term objectives are increasingly shaped by the values of these NewSpace companies. In each case, American NewSpace executives have demonstrated an ability to influence their environment, especially by beginning to incorporate traditional contractors into their business model. Each company now focuses on market competition as their driving force, rather than meeting the niche needs of state programs (MHI), making launches safer and more reliable (Arianespace), or supporting NASA's exploration program (Boeing).

6.4.3 Infrastructural Momentum: Vertical Integration

Infrastructural innovations, such as vertical integration, contribute to the momentum of private spaceflight along with the plethora of new software and hardware components. Vertical integration takes several stages of production which are normally conducted by separate companies or organizations (horizontally) and integrates them into a single company or organization, aka vertically. For example, SpaceX manufactures all of their launch vehicle's components in-house, contracting only for labor (Shanklin 2013). ULA has begun moving closer to this organizational model (Anonymous 2017), indicating that they at least believe that such vertical integration confers some advantages to SpaceX. Orbital Science, now Orbital ATK, pioneered this organizational innovation. They manufacture satellite parts, own and operate satellites, launch satellites, and provide technical support for satellite systems. Each of these companies controls at least some aspects of every part of the production process.

General Electric used a similar strategy to control the electric light and power systems of early 20th century America. In 1905 they established the Electric Bond and Share Company (EBASCO) which was an electric utility holding company that "provided financial, management, and engineering construction services to the utility companies" (Hughes 1994, 105). General Electric used EBASCO to coordinate the construction of equipment to fit the specific needs of the utilities they held. This coordination was rather complete, as "EBASCO management recommended construction that EBASCO engineers carried out and for which EBASCO arranged financing" (Hughes 1994, 105). All of this integration meant that local, state, and even federal governments had a stake in the EBASCO system because they had an interest in the utility to which EBASCO was integral. Engineering organizations and schools had economic interests in the EBASCO system, and so too were committed to its continuation. EBASCO's coordination increased the number of other industries and companies with which it interacted and thus also increased economic interest in its continuation.

The momentum of private spaceflight companies increases through similar mechanisms. First, vertical integration centralizes authority, which reduces the ability of outside forces to influence the trajectory of development within these private companies. Vertically integrated companies have to negotiate with many fewer contractors and suppliers, allowing executives to make changes much more quickly and without bargaining or discussion with outside interests. Second, vertical integration also invests laborers into the expansion of private spaceflight through economic means. For example, even though Elon Musk's management style of "nano-management," attending to even the minutest details of the jobs of each of his employees, results in employees who are overworked and whose creativity is stifled compared to similar positions elsewhere, it has become very beneficial for employees to at least begin their careers at SpaceX. The experience in multiple stages of development and the rigor from vertical integration are deemed benefits for future employers (Anonymous 2017). As more companies adopt a style of vertical integration in response to the dominance of economistic values in spaceflight, it will become increasingly difficult for engineers seeking employment in aerospace to work in a different environment. By reducing the prospect for outside control and steering, and increasing the economic dependency of other groups, like labor, in the development trajectory set out by these private spaceflight executives, vertical integration is an organizational innovation that increases the momentum of their vision for spaceflight.

6.4.4 Expert Momentum: Whose Problems Get Solved?

Private space executives have begun to make technical expertise more easily applicable to solving problems that best align with their own interests. The crux of the creation of technological momentum is solving problems of efficiency called reverse salients. Therefore, whichever groups can direct the labor of experts towards solving their problems are most likely to accumulate the most momentum in their favor.

As Edison's system began to grow, and thus the demand for experts in electrical systems increased, schools for engineering responded by increasing the available opportunities for training in electrical engineering. Before Edison's DC power system, electrical engineering was not offered as a specific subfield of engineering education, but developed into one afterwards. Edison took full advantage of this, presenting his findings at electrical engineering conferences and thus influencing the direction and interest of the field even more. As the field oriented itself to support Edison's system, they passed this orientation on to students through burgeoning electrical engineering programs (Hughes 1983, 142–60). Any challengers to Edison's system would not only have to overcome technical, legal, infrastructural and other obstacles, but they would also have to overcome an entire profession trained and financially enrolled in the operation of the DC power system.

In the case of spaceflight, several disciplines already exist which can support the technical aspects of a large variety of space development pathways. But executives have already begun to specialize and direct at least some part of this existing expertise. Embry-Riddle Aeronautical University now offers a Bachelor's of Science in Commercial Space Operations (Embry-Riddle Aeronautical University 2017), training the next generation of engineers to work within this system of private spaceflight. Private companies also employ several other methods to direct experts to work on the problems deemed important for privatization. Several conferences, for example Space 2.0 (Infocast 2016) and the NewSpace Conference ("NewSpace 2017" 2016; Dayal 2017), support the coordination and sharing of knowledge between actors within this system. Executives also offer extra resources for experts who work on their prefered problems in order to further direct technical development. Utilizing the prize model pioneered and demonstrated by NASA, both the Ansari X Prize ("Ansari XPRIZE" n.d.) and the Google Lunar X Prize ("Google Lunar XPRIZE Home Page" 2017) provide monetary incentives and support where resources may otherwise be withheld.

Furthermore, the perpetuation of reusability strategies not only expands the technical momentum of privatization, but also the expert momentum. Each new artifact or piece of software required for each of the various full or partial reusability strategies requires engineers and other experts to solve problems. Much like Edison's system, these new and interesting problems attract an increasing number of engineers to work on private spaceflight systems, rather than for alternative visions of spaceflight. Their findings get presented at conferences such as the Space Symposium in Colorado Springs, or the annual NewSpace Conference. This orients the necessary fields of engineering and science to focus on the problems important to the specific vision for spaceflight held by private spaceflight executives, which is then passed down through education to future engineers. The problems these executives identify are interesting to aerospace engineers, software engineers, computer scientists, mechanical engineers, electrical engineers, physicists and many others as well. While Edison enlisted the field of electrical engineering, private space companies seek to enlist engineers from a wide variety of fields to share in their economistic vision of spaceflight and space development.

6.4.5 Legal Momentum: New Laws and New Contracts

Legal innovations also extended the momentum of private spaceflight. NASA administrators created new types of funded contracts in response to the looming threat of losing human spaceflight capabilities after the space shuttle retirement. In response to this dual threat of the so called "human spaceflight gap" and chronic underfunding, NASA administrators began making funded Space Act agreements (SAAs) to develop commercial cargo capabilities to the ISS (Bretton Alexander 2013). Upon the recommendation of the Review of United States Human Spaceflight Plans Committee (Augustine Committee) in 2009, this new type of contract was expanded to develop human spaceflight capabilities as well (Augustine et al. 2009). But what are SAAs and what makes them different from previous types of contracts?

Traditionally contracts have been completed on a cost-plus basis, but NASA officials describe funded SAAs as more akin to business investments (Alan J. Lindenmoyer 2012; Gerstenmaier 2013). Private spaceflight executives viewed cost-plus contracts as a barrier to more efficient participation in spaceflight by the private sector because of the requirements companies must meet to compete for those contracts and what these executives perceived as NASA interference in the operation of the final product. NASA also saw SAAs as a way of solving the reverse salient between organizational goals and funding allocations for those goals. Both groups saw inefficiencies, or reverse salients, that could be solved through a legal innovation.

What did SAAs change? The cost plus system requires the agency to pay for the cost of the contract and then an additional set payment on top of that, which is how contracting companies make a profit. In order to prevent problems such as politically favored companies being awarded contracts or companies bloating costs to get larger contracts, all cost plus contracts operate under Federal Acquisition Regulation (FAR). The FAR requirements do, however, entail some degree of bureaucratic overhead that limits the ability of small companies to participate, such as certified pricing systems and demonstrated health and safety procedures (Alan J. Lindenmoyer 2012). NASA also typically dictates requirements in cost plus contracts because NASA usually operates the final product. Both of these problems, as perceived by private spaceflight executives, change under SAAs. Instead, NASA uses SAAs to invest in a future service, the development of which is already underway. This means that NASA does not pay the full cost of development, but also that NASA does not dictate requirements. Operation of the vehicle is also not turned over to NASA after development. So, because NASA is therefore theoretically only one customer among many, they must choose between existing options rather than developing a new launch option to suit their specific needs. NASA instituted two funded programs using this model: the Commercial Orbital Transportation Services (COTS) program and the Commercial Crew Development (CCDev) program. COTS developed capabilities for resupply of the ISS, and CCDev develops human spaceflight capabilities. These legal innovations in the relationship between NASA and the private sector solve the perceived inefficiencies of cost-plus contracts by giving more authority to private industry actors to dictate design and operation, and releasing them from many of the FAR requirements.

Electric utilities, following Edison, used similar legal tactics to increase their momentum and their influence. In 1907 the National Electric Light Association (NELA), an electric utility trade organization, utilized state level regulations for this purpose. At this point, municipally owned utilities were threatening the expansion of private utility companies. To counteract this trend, NELA advocated for state regulation of rates and services at levels favorable to private utilities. By moving regulation to the state level, local governments could no longer regulate favorably to the municipal utility. State governments, instead, regulated according to the advice provided by private utilities. Thus, NELA was able to relegate political authority as subservient to those of electric entrepreneurs (Hughes 1983, 206–8).

SAAs generate momentum through similar processes to the NELA. First, by preventing NASA from terminating the contract outside of preset conditions, it shifts political authority to private executives. This is similar to the shift in political authority that resulted from state rather than municipal regulation of utilities. Second, by increasing stability and attracting investors, it centralizes the interests which have decision-making authority, replacing the interested public with shareholders and venture capitalists. Third, by increasing the ease with which NASA services can be sold to other customers, SAAs reduce the influence of NASA over spaceflight development goals. If companies are not beholden to outside interests, they can accumulate a great deal of momentum. Finally, the most important innovation for private companies is reduction in costs by reducing overhead costs. For example, the overhead of the COTS program was only 3% (Alan J. Lindenmoyer 2012). The whole point of the innovation of funded SAAs is to "lower the cost of access to space" (Garver 2013). Much like the strategy NELA utilized, SAAs look like a good deal for governments, but they prioritize monetary considerations over other potential values, such as reliability, international cooperation, or scientific return, and, most importantly, places government actors in subservient roles to private actors. This ensures the continuation of the economistic focused private spaceflight system, growing its momentum.

Laws are also enlisted in the strengthening of private spaceflight by providing beneficial legal frameworks. The Commercial Space Launch Competitiveness Act of 2015 (McCarthy 2015) is an ideal framework for private spaceflight companies. This act includes three provisions of exceptional importance. First, it extends until September of 2025 government indemnification of third party damages beyond a "maximum probability loss" (McCarthy 2015). Importantly, this includes a cross-waiver of liability between launch providers and their customers that, critics argue, would "provide launch companies with immunity from civil actions in the event of an accident" (Foust 2015). Second, it extends restrictions which prevent the government from enacting new safety regulations until 2023 (McCarthy 2015). This period, known as a learning period, is designed to ensure that companies can make mistakes without going bankrupt, with the ostensible purpose that they be able to learn from those mistakes and make spaceflight safer and more reliable in the long run. Finally, the bill allows ownership by citizens of “any…space resource obtained” including the right to sell that resource (McCarthy 2015). Land ownership is excluded in order to avoid violation of the Outer Space Treaty, which prohibits national appropriate by claim of sovereignty (*Outer Space Treaty* 1967). However, it remains unclear whether even this language violates the Outer Space Treaty.

This law enhances the conditions for momentum, yet how will it stand up to legal scrutiny given the ban on national appropriations in the Outer Space Treaty? The Outer Space Treaty of 1967, the primary international treaty dictating space law, states in article two that “outer space, including the Moon and other celestial bodies, is not subject to national appropriation by claim of sovereignty, by means of use or occupation, or by any other means” (*Outer Space Treaty* 1967). Many scholars of space law interpret this passage to prohibit the ownership of any kind of space resources (Tronchetti 2014; Delgado-López 2015; Tronchetti 2015). Arguments range from the necessity of state sovereignty to support property rights (Pop 2000), to the necessity of claim to the object in which the resources are found in order to claim the resources (Sterns and Tennen 2003). The most common interpretation is simply that the situation of legal ownership in outer space is unclear (Rathman 1999; Coffey 2009). Without a ruling by the supreme court or the United Nations International Court of Justice, the legality of space resource ownership, and thus of this law, will be unclear.

The purpose of the Commercial Space Launch Competitiveness Act, then, could be interpreted as politicians’ effort to preempt legal action by building enough momentum behind the law to force a business friendly interpretation of the legality of property rights: legal clarity through the creation of momentum. Private space development companies may have a difficult time attracting investors if the legality of their business in unsettled. Among other things, this legislation acts to at least signal congressional support, and possibly establishes legality.

However, the law may not provide that stability if it is deemed in conflict with the Outer Space Treaty. Thus, business leaders hope that the legislation provides a legal framework that other nations may replicate.

6.4.6 Momentum's Barriers to Alternatives

What are some strategies that might make more revolutionary responses to reverse salients more likely? Studies in the social construction of technology (Bijker, Hughes, and Pinch 1987) show that *social groups* define the problems that new technologies solve. The interpretive flexibility present in the initial stages of technological development eventually come to closure because certain social groups are able to dominate, effectively defining the development of the technology in question (Pinch and Bijker 1984). Without enough competition between social groups, closure can occur too early to pursue alternatives as momentum begins to build. Therefore, involving a diversity of interested groups is more likely to increase the diversity of potential solutions (Lindblom and Woodhouse 1993; Sclove 1995; Woodhouse et al. 2002; Woodhouse and Sarewitz 2007; Eubanks 2007). If combined with an appropriate distribution of decision-making authority (Harding 2006; Woodhouse and Sarewitz 2007), this strategy is likely to decrease the accumulation of technological momentum.

For example, although some NASA officials describe SAAs as a revolutionary innovation where NASA "invests" in private companies rather than giving them contracts that encourage over-spending (Alan J. Lindenmoyer 2012; Gerstenmaier 2013), SAAs are not really investments. NASA does not get rewarded with shares of the company, does not get a return from company profits, and does not get votes on the board. Funded SAAs might better be described as a different way of organizing cost sharing, where the amount that NASA puts toward the project is set beforehand, and contingent on certain goals. Funded SAAs are effective at solving the inefficiency for NASA of ballooning budgets, but are more effective at solving inefficiencies for private executives: designs made to achieve NASA objectives rather than private ones, and FAR regulations creating an effective minimum size for companies that wish to participate. They thus create momentum for systems of spaceflight which rely on privatization. But what if they actually were investments? What if in exchange for their investment, NASA received shares of the company and got a percentage ownership, with all the benefits thereof?

One potential result of such a change might be to increase the number of relevant interests included in decision making before closure. The resulting board votes could be used to diversify the interests represented. Certainly NASA could more easily direct the company to focus on some of the public oriented goals of NASA, such as research and educational outreach, if NASA filled some of those seats with their own bureaucrats. But the process could also be made more democratic if those seats are appointed by elected officials, or if those positions are directly elected. They would thus both represent the interests of various publics and also be assured comparable influence with industry actors for comparable monetary contributions.

NASA might also simultaneously incentivize innovative pathways which are marginal, intentionally supporting divergent approaches. For example, if most private companies are focusing their development on technological innovations which make their vehicles more market competitive, such as chemical fuels that better balance efficiency with price or more efficient reusable engines, NASA might provide support to companies focusing on a completely different set of technologies. For example, the company Ad Astra, founded by former astronaut Change Diaze, focuses on the development of plasma engines called the Variable Specific Impulse Magnetoplasma Rocket (VASIMR). Rather than an engine that is cheaper to run, the company hopes to innovate an engine that is more energy efficient at relatively fast speeds of travel. The company also has non-market, non-technical priorities that NASA might do well to promote alongside market and technology oriented priorities. Ad Astra located their plasma lab in Diaze's home-country of Costa Rica and hire locals based on factors aside from expensive technical educations. For example, their head machinist was previously employed at a gas station, but was hired because of their aptitude for learning and enthusiasm for the work (Upson 2009). Private companies are unlikely to innovate based on factors related to these sorts of social goods without some incentive, and these incentives clearly do not need to come at the cost of quality technical innovations.

The rapid pace of technical and organizational innovations in contemporary private spaceflight contributes mostly to increasing the momentum of that technical system. These innovations change little of the underlying values inherent in private spaceflight, nor do they create a competing mode of operation that could allow the pursuit of alternative development. For example, while private companies focus on organizational innovations that reduce costs, it might instead be equally feasible to innovate new organizational forms that make international cooperation easier. Each of the innovations analyzed in this chapter increases the control and authority of private spaceflight companies and executives, thus contributing to momentum which is now increasing as rapidly as these new innovations are being produced.

6.5 Potential Consequences of Momentum

Given the size of many of the traditional aerospace contractors, how did NewSpace companies manage to so thoroughly shape space policy to *their* advantage? The leaders of these companies might claim that they innovate and compete where traditional contractors have become complacent. As the previous section has argued, the pace of innovation, and the entrenchment of bureaucracies, laws, policies, and organizations certainly contributes to the development of a momentum to rival that of traditional aerospace contractors. An increasingly large proportion of spaceflight is beginning to look privatized. A plethora of new private companies, new support industries, new laws, and the inclusion of new government agencies have made it difficult to resist the privatization of spaceflight. Even those traditional aerospace contractors have shifted to mimic these new companies with the mounting pressure of their momentum. While the chapter so far has analyzed what momentum is and what momentum creation looks like in the realm of spaceflight, this section will examine the consequences of increasing momentum of private spaceflight.

Edison did not create momentum for his electrical system by merely innovating. He actively attempted to enroll laws, companies, and regulations into his system. For example, Edison tried, in several states, to outlaw electricity transmission over a certain voltage (200-300 volts depending on the legislation), which would essentially negate the advantage of long transmission distances for AC power (Hughes 1983, 108). Even when it became clear that AC systems were technically superior to DC systems after the invention of transformers and AC motors, the investment in DC systems in urban areas was too large for utility executives to justify a switch. Even just phasing out the DC system for an AC system would have negated the advantage of scale from using a single system, thus discouraging utilities further. Furthermore, manufacturing companies and investment companies were committed to DC power through investment in patents, expensive equipment, and experts educated to operate DC power systems. Their caution against losing this investment before knowing that AC would be dominant was, in effect, support for the status quo of DC power systems (Hughes 1983, 120). Edison had successfully set up a system that prevented those actors enrolled in it from attempting to pursue any other development. Essentially, Edison had created a barrier to improvements in electrification. What sorts of strategies are being used to support privatization? What are implications of these strategies and for whom?

When Edison was creating his electric power system, he proficiently utilized licenses for his patents to ensure that his DC electrical system was adopted by a large variety of customers, ensuring it became necessary for many daily tasks. Most obvious is the use of arc lighting in cities, making city lighting systems dependent on DC power. Moreover, motor manufacturers created DC motors for everything from streetcars to elevators. As such these modes of public transportation became dependent on DC power systems. Early appliances were usually battery powered, until manufacturers began using DC motors instead, hooking them into the DC power grid and into the influence of the DC power system (Hughes 1983, 82). This intentional creation of a dependence on the DC power system through new technological artifacts increased its momentum, making it more difficult to switch to an alternative without significant alteration to other systems.

Both SpaceX and Blue Origin intend to utilize the reusability of their launch vehicles to dominate space based transportation infrastructure. Musk hopes to use his company’s barge landing technique to offer fast, long distance travel around the globe (O’Kane 2017). Both Musk and Bezos say of SpaceX and Blue Origin respectively that they want to build the launch infrastructure upon which the future of space exploration is based (Bezos 2017). If going to space soon becomes dependent on these companies, they will have created a system similar to Edison’s DC power system, where multiple related industries will be dependent on its expansion. However, it need not be SpaceX or Blue Origin specifically. Private companies, economically incentivized as they are, seem likely to make meeting those economic incentives a central part of any future space development so long as they control the infrastructure required to access space.

With each new innovation it becomes more difficult for others to pioneer something truly revolutionary. Each new component represents a new set of interests enrolling a new set of actors. Manufacturers have a financial interest in continuing to make these new engine components. Satellite operators rely on the launch systems enabled by these new components to launch their satellites. In general, it is easier for other parties to innovate new ways to use these existing components than it is for them to both innovate new components AND come up with some profitable or desirable use for them. Given this, it becomes clear that one should not expect private companies to create revolutionary innovations. They are disincentivized to do so because the added difficulty of selling revolutionary innovations makes it difficult to convince investors to fund the project. Thus, as spaceflight becomes more privatized, observers should expect momentum to increase somewhat, simply from the predisposed interests of private executives towards conservative innovations.

Increases in infrastructural momentum can also impact the quality of decision-making. Recall inflexibility, scholars studying inflexibility (Collingridge 1992; Genus 2000) have noted the negative impacts of centralized decision-making on the ability to respond to and prevent errors. Centralization negates the need for debate, with two main consequences. First, by limited the total number of perspectives offered, it prevents potentially important insights, thus increasing the likelihood of failure. Second, by limiting the number of interests involved, centralization places substantial barriers to correcting those errors because unaffected interests are both unlikely to notice the error in a timely fashion and have fewer incentives to correct it. Thus, since the whole purpose of vertical integration is to increase control via centralization, this innovation which leads to momentum clearly falls prey to the negative consequences of inflexibility.

Recall Chapter 4, in which I discussed the creation and consequences of lock-in. This chapter posed the problems of too few organizations controlling access to space resources. Imagine if one or two space companies are deemed "too big to fail." The 2008 financial crisis had massive consequences, but what if those companies controlled nearly every aspect of the fate of an entire planet's population? Smaller examples are the Space Shuttle. Over budget and prone to schedule confusion, the centralization of decision-making on the Space Shuttle made it increasingly difficult for NASA to identify and rectify errors. This played an important role in the shuttle's two disasters (Collingridge 1990, 1992). Alternatively, the development of the UK's North Sea Oil industry was determined largely by a small handful of oil executives who made wrong, but unquestioned, assumptions about the market for oil and the costs of development. These hasty and uncontested decisions nearly spelled ruin for the energy economy of the UK if it weren't for a fortuitous and unforeseen spike in oil prices (Genus 2000). These examples indicate the results of centralization and inflexibility. Turning from such a course requires outside influence over the companies in question, such as SpaceX or Blue Origin, and the increased centralization and momentum resulting from vertical integration presents a barrier to that influence. The ability to steer important space development activities in any direction other than those preferred by powerful executives relies on decentralization and therefore on reducing the momentum caused by vertical integration.

Nor is expertise passively evolving to fit some inevitable future of space development. Executives, as well as bureaucrats and politicians favorable to privatization, are actively enlisting experts into furthering the dominance of market oriented values over space development. They are directing expertise to establish a firm and difficult to alter infrastructure supporting their vision for the future of spaceflight. Recall again the case of Edison. Even as AC power began to replace DC power, it took several decades for electrical engineers to catch up. Their curricula had been designed by engineers with direct interest in the success of Edison's DC system. By the time it was clear that the system had failed, it was too late to easily change the institutions of education throughout the world which had already been designed. Manufacturers of new polyphase (AC) generators complained that electrical engineers were too versed in theory and didn't know enough about how to apply it: a direct result of their DC oriented training (Hughes 1983, 142–44). If a similar situation arises in spaceflight, where it becomes clear that priorities aside from those held by spaceflight executives offer more widespread benefits, will contemporary engineers be able to offer their expertise to those new goals? More likely, they will be stuck, just like Edison's electrical engineers, and their narrowly designed expertise will serve more as a barrier than an enabler of space development.

Legal consequences, too, abound. SAAs, by increasing the momentum of private spaceflight, have two major outcomes. First, they reduce the ability of outside interests to impact the direction of spaceflight development. Few people have direct interaction with the exploration and development of space compared to other areas of technological development, but as space development continues more and more groups will find they need a say. If momentum has become too large it will thus exclude many different groups from making decisions that impact their lives. For example, new uses for outer space will be limited to those which spaceflight providers are willing to support. Workers seeking to improve their lot may find terrestrial laws unhelpful. Colonists who wish to change the way they are governed may find themselves without the power to do so. Second, SAAs decrease the ability to make beneficial changes. With fewer interests involved in decision-making about spaceflight, it will be more difficult to identify errors. For example, reusability may save quite a bit of money, but if the increased complexity primes launch vehicles for normal accidents (Perrow 1981) the interests of a company like Blue Origin may not entice them to examine that possibility. Even if errors are found, reducing the influence of outside interests also reduces the impetus to correct them. If SpaceX executives, for example, are not harmed by an error they are less likely to address it. But if those who are harmed have some say in decision-making, it is more likely to be addressed.

NASA executives have also framed the funding structure pioneered through SAAs as an *investment* in companies trying to provide potentially useful services (Alan J. Lindenmoyer 2012). However this funding is not an investment, as NASA does not get any ownership share in exchange. Funded SAAs allow private companies to receive funding from NASA without having to submit to NASA requirements and extra regulations that go along with FAR contracts. Without this funding, some participants, like SpaceX would not have enough capital to operate (Berger 2016a). Most of the companies involved profit primarily off of services to government agencies. Traditional contracts at least require private companies to contribute towards public programs. Funded SAAs do the reverse, where NASA becomes enlisted as a supporter of private development programs on the assumption that NASA may benefit down the road, but only in as much as any other customer would benefit. Therefore, NASA has become enlisted in private spaceflight via COTS and CCDev through the mechanism of funded SAAs.

This strategy is working. In February of 2016, Luxembourg announced its own plans to model space development legislation there on the American law (Zenners 2016a). Luxembourg is a particularly important country in this regard because it is the home of Société Européenne des Satellites (SES), which is the largest satellite operations company in the world (SES SA 2017). The company operates more than 50 satellites, controlling the majority of satellite broadcast and communications on every continent (SES SA 2017). This makes the small Grand

Duchy of Luxembourg one of the most important countries in terms of private space development. Sagi Kfir, the chief lawyer for Deep Space Industries (DSI), an asteroid mining company, described the news of Luxembourg's forthcoming legislation as "evidence of the unstoppable momentum of the asteroid mining industry" (Shaer 2016). He observes "first the U.S., and now Luxembourg. I think the genie is out of the bottle…For the next year or so, you might have lingering opinions on whether this is legal, but after a while, as more countries join and have their legislation, that will stop" (Shaer 2016). Luxembourg has already signed memoranda of understanding with both DSI and Planetary Resources (Zenners 2016b, 2016c) and invested $227 million in a fund to attract asteroid mining companies to locate there (Morris 2016). Already the United States and Luxembourg have become enlisted into the legal aspect of the technology of private spaceflight. This alone substantially increases the momentum of market governance. If, as predicted, other countries follow suit, then the momentum can be expected to build up to the point that it will be exceedingly difficult to substantially alter the legal framework for space development. It cannot be known what the consequences of legal ownership of space resources will be. Therefore, if this is the direction in which decision makers choose to proceed, it would be better to do so using a legal framework that is not designed to prevent changes, in case those consequences are unbearable.

6.5.1 Reducing Size

Reducing momentum means, to some degree, reducing the scale and complexity of technological systems. One strategy is not necessarily to stop the growth of the private space industry, but simply to slow it down enough that the pace is more manageable for decision makers to identify, analyze, and mitigate potential problems and errors as they arise (Woodhouse 2016). This section, and many of the other chapters, has demonstrated the importance of government support for the success and continued innovation of the private spaceflight sector. Thus, there is still genuine opportunity for public intervention. By utilizing strategies suggested by reconstructivist scholars (Woodhouse et al. 2002; Woodhouse 2005; Hess 2007), in particular, the framework of Intelligent Trial and Error (J. G. Morone and Woodhouse 1986; Woodhouse and Collingridge 1993), I will suggest several strategies which could be implemented to slow down innovation.

First, NASA could be more judicious about funding spaceflight innovation. For example, while the BEAM module might someday be useful to NASA as a cheaper way to build the next space station, such a project is not on the horizon, and NASA's resources might be better spent allowing other companies to test their innovations using NASA resources. Second, NASA might simply allocate less money to fund development in private spaceflight, and use more of it on their own projects. Other strategies include targeted incentives to private companies to more strategically steer space development. For instance, indemnification might only be offered to companies meeting some sorts of milestones over others. Adding democratic mechanisms such as citizen panels, town halls, or public comment to determine what milestones warrant such rewards would be all the better for keeping momentum small.

Of course these expeditious innovations occur, in part, because it benefits executives to do so, and those executives have massive discretion over the behavior of private spaceflight companies beyond even merely responding to market cues. Many new legal innovations add to this discretion. Funded SAA's, for example, relieve pressure from CEOs to respond to NASA's needs directly. Innovation may be kept slow enough to reduce momentum if NASA administrators are left a greater share of authority, but this is hardly a guarantee. Ideally, a mix of democratic methods controlling the direction and pace of development would be best, but a more immediately useful change to slow innovation could be to channel the interests of those executives. Perhaps if CEOs of companies which receive funding from NASA had at least some part of their salary depend upon meeting public goals for innovations that would provide sufficient motivation to steer innovation in that direction (Woodhouse 2006). This goal could be modified to slow innovation by directing CEOs to invest in a greater diversity of potential innovations, increasing the likelihood that some of those pathways are duds, but also increasing the likelihood of catching potential errors early, and decreasing momentum. In general, while it would mean longer time scales for many space exploration goals, the trade off of reducing momentum may be worth slowing down the pace of innovation among private spaceflight companies.

However, much industry support is out of NASA's hands. The Commercial Space Launch Competitiveness Act provides several supports for private companies, such as indemnification and a ban on new regulations. While the bill seems to be accomplishing its goals, it does so at the cost of incentives for correcting errors, funds to ease consequences of errors, and regulatory monitoring that might find errors. Future policies would do well to focus on error correction. Although the bill calls the moratorium on new regulations a "learning period," it actually prevents learning by acting as a barrier to error correction. Establishing a real learning period would require: limiting the scale at which development companies can operate in order to limit the severity of the consequences of errors, requiring scale-up to occur gradually in order to improve the likelihood of catching errors before they become large, and prioritizing innovations and other ideas that could be tested quickly i.e. where errors would reveal themselves sooner rather than later (Woodhouse and Collingridge 1993). Given that the social consequences of errors might reveal themselves well into the future, for example governance problems with new space outposts, and that such consequences are more difficult to assess than technical ones, for example it is harder to determine if infrastructural dependence is too high than it is to determine if heat thresholds on thermal tiles are too low, these strategies would substantially slow down the pace of space development. Privatization is becoming more prevalent, with an increasing number of components contributing the private spaceflight.

In addition to the new technological and organizational components discussed in the previous section, this section has analyzed the contribution of an increasing number of private companies and support industries. Governments, the U.S. government but increasingly others, have also been enlisted in support of privatization. The Commercial Launch Competitiveness Act attempts to force legal clarity of the Outer Space Treaty by increasing the momentum of private industries which would benefit from property ownership. Some companies hope that other countries emulate the law so that its interpretation of the treaty becomes established internationally before some other legal evaluation is brought to bear on private resource rights in space. So far this has been somewhat successful, as Luxembourg, a prevalent nation in the satellite industry, has created similar legislation. The prominence of this market orientation towards spaceflight has even affected contractors around the world, shifting their priorities to be more responsive to market values, such as reducing costs, and market competition. This increase in the number of supportive technosocial components makes it much harder to shift development direction because it increases technological momentum.

6.6 Conclusion

This chapter has applied Hughes's concept of technological momentum (Hughes 1969, 1987a, 1994) to contemporary private spaceflight. The analysis of this chapter has found a steadily increasing momentum of private spaceflight and space development. Rather than addressing problems in new ways, private innovations are conservative solutions to the reverse salients of spaceflight. As such, these new innovations do not diversify the possible directions for spaceflight development but entrench established ones, namely those which make spaceflight more profitable. I have also demonstrated in this chapter how increasing momentum acts as a barrier to learning by making alternatives much more costly to pursue. As privately controlled space missions become more prevalent, it will be more difficult to have publicly controlled ones, or those that meet the needs of any other partisans with an interest in the outcome of space development. The number of technological, organizational, infrastructural, expert, and legal components that support privatization within spaceflight have increased, and even those organizations that had resisted such change now seem to have little choice but to adapt to an increasingly privatized space program. The increasing momentum of private spaceflight will make it difficult to alter the trajectory of space development or the speed at which it occurs.

The goal of this chapter has been to analyze the momentum of private spaceflight to better understand how momentum contributes to obduracy as a barrier to alternative configurations. What inefficiencies with spaceflight are important to which actors? How conservative are the innovations being made by private industry? Do these innovations increase the diversity of ways in which spaceflight might be conducted? What values or goals do these innovations promote? How diverse a set of interests do such innovations support? How do these innovations impact the ability to proceed intelligently via trial and error? What mechanisms might be useful for reducing or slowing the growth of momentum?

In his work, Hughes has identified a process for the formation of technological momentum which this chapter has used to analyze the development of private spaceflight. I analyze the above questions by identifying reverse salients from NASA RLV programs, then analyzing how innovations by private industry have addressed these reverse salients. Momentum is the result of growth and consolidation, i.e. an increasing number of artifacts etc. which tend to promote one partisan group over others, which does not occur in all technological systems (Hughes 1987a, 69–80). The key to whether growth and consolidation will result in increased momentum, however, lies even earlier in the development process. Hughes argues that innovations which solve reverse salients eventually lead to growth and consolidation, while those that do not usually result in alternative technological systems and competition (Hughes 1987a, 72–76). This chapter has used this process as the basis for evaluation of private spaceflight innovations. First, I used a historical analysis of NASA RLV development programs to identify reverse salients. Then I compared a set of innovations that have been most heavily promoted by their respective companies and identified by industry actors as being most important to these reverse salients. Through this analysis this chapter has found that these innovations do not alter trajectories of technological development. They do not demonstrate alternative ways of looking at the problems posed by reverse salients. Instead, they apply similar conservative solutions.

By breaking down the components that add to momentum into five dimensions, I have also shown how spaceflight executives utilize more than just new technological artifacts to cement their control over spaceflight and build momentum. New organizations designed to support their preferred way of doing things, new laws which effectively exclude alternatives, changes in infrastructure to centralize authority, and altering the development and dissemination of expertise to be more narrowly useful have all also contributed to the momentum of privatization. Private spaceflight meets Hughes's criteria for technological momentum.

Moreover, in the continuous theme of learning present in this dissertation, momentum acts as a barrier to learning and thus a barrier to less risky and more broadly beneficial development. Despite its name, technological momentum is not purely technological. Momentum does not just reduce prospects for steering in general, it reduces the prospects for outside influence over a system which has become effectively dominated by a single, or at least very few, interest(s). Without changes in who conducts space development and how they do so, it will become very hard in the future to alter its trajectory to alleviate consequences to those who have been excluded.

Momentum is the final facet of obduracy. Previous chapters have focused on how aspects such as decision-making, historical factors, interactional dynamics, interest groups, exclusion, and agendas can erect barriers to selecting alternative systems of technological development. This chapter has rounded out these factors by focusing on how the components of technological systems themselves contribute to such obduracy. As a whole, the four facets discussed in this dissertation together show the ways in which obduracy is a barrier to open and flexible technological development. Specifically, these chapters have shown how obduracy is a barrier for re-choosing how humanity goes about expanding into outer space. Momentum is the final facet that prevents the ability to alter our decisions should we find out they are, for some reason, regrettable.

7. Conclusion

7.1 Summary

This dissertation has analyzed the particular barriers from obduracy which inhibit reconstructing contemporary policies for space development should it turn out that economistic governance is not the boon many policymakers predict it will be. It has shown that each facet of obduracy makes reconstruction and reconsideration more difficult, and that private spaceflight shows signs of growing obduracy. The policy position that future space development should be governed via economistic mechanisms was not explicitly made through democratic or other deliberative decision-making processes. Instead such economistic governance was the result of an accumulation of events, decisions, and factors not directly related to this goal nor explicitly intended to achieve it. This policy position is becoming locked in to the operations of both state bureaucracy and private companies, it is beginning to exclude alternative pathways of development driven by alternative partisan values, and shows rapidly increasing technological momentum (Hughes 1987a, 1994).

But what might prove so bad about private space development? How might the future of spaceflight proceed differently based on taking more malleable or more obdurate approaches to development? The answer lies in the ability to respond to problems and to distribute benefits. Let us walk through the possibilities of both styles of development.

First, thinking about near-term development, spaceflight executives have utilized obduracy to centralize control over decisions regarding space development. Thus, for the most part, the success or failure of the endeavor, and what counts as success or failure, are dependent on only a few select individuals without any substantial input from other citizens groups. Not only does this limit the ability of spaceflight to meet the goals of other social groups, but it limits even what NASA’s public program can accomplish by establishing a dependence on private services. A more malleable approach would distribute decision-making authority more broadly. NASA might pursue a larger variety of strategies aside from privatization to prevent such dependence, and employing a larger variety of decision-making mechanisms including more groups would prevent centralization and the barrier to learning that centralization erects.

Moving further out in time, I will address the initial stages of extraterrestrial development. The initial stages of private space development might include activities like “cruises” to Mars supported by resources obtained from asteroid mining. Inflatable habitats like those made by Bigelow might provide shelter both for such private trips, but also for publicly funded space stations and lunar bases, as well as asteroid mining operations and orbital hotels. Some of these endeavors might fail and others might not, but they would not fail because of the harms they do to one group or another. Rather they would only fail if they were unprofitable, that is, only market mechanisms would cause failure. In other words, the only mechanisms by which success or failure would be judged is monetary; endeavors fail if they don’t make money, and succeed if they do. Their success will thus be independent of problems such as: working conditions, pay, risks presented to passengers, increases in consumption levels, environmental impacts, or any number of other myriad concerns that partisans might rightly bring up. A more malleable, or at least less obdurate approach, would diversify the number of oversight mechanisms through which to identify errors, and would also diversify the number of mechanisms that incentivize error correction. While market mechanisms are a very efficient way to coordinate resources in order to achieve a particular objective, in this case it lacks efficient modes to identify errors and sufficient incentives to correct them. A more malleable approach would utilize a variety of different strategies to ensure that, for example, the pleasure cruises SpaceX might offer to Mars are not reliant on abusive and dangerous working conditions for the crew, or that increased consumable goods from space don't simultaneously increase waste-based pollution on Earth.

Looking much further in the future, how might the current obdurate system of development differ from a more malleable approach? It is clear at this point that Mars is the only destination under consideration for permanent human habitation, especially because it potentially allows very large scale habitation. But what if the scale of that habitation presents a problem? Perhaps the resources necessary to keep a Mars colony going are so large as to be strain on some terrestrial peoples even though it generates a great deal of wealth of the company running that colony? Or what if development cannot keep up with emigration and colonization creates massive slums? Or perhaps, again, the extraction and/or disposal of resources creates an environmental problem either on Mars or Earth? The current obdurate system offers no incentive to change and, in fact offers disincentives even if the problem is obvious. Taking a more malleable approach would require taking more time beforehand to learn about and analyze potential alternatives. It would also require preparation to initiate those alterative should the chosen path not work out. For example, before selecting Mars as a colony, a great deal more research would have to be done on Venus, asteroids, or LaGrange points to ensure that they might not be better options for some social groups. Then, when a destination is finally selected, it should be done with a clear path for alteration in mind should it not work out. For example, perhaps the technological and physical limitations of a colony on Venus would actually prevent some of the above potential problems that might crop up with a Mars colony. We cannot now know if this is the case, but that is entirely the point! A more malleable approach ensures a certain level of preparedness for the inevitability of unforeseen consequences.

Large space organizations are restructuring themselves to adapt to governance by market mechanisms, and the technological artifacts they create have those politics built into them. Recall, how three different major launch companies across three continents, ULA, Arianespace, and MHI, all altered their strategies and goals and even the very designs of their next launch vehicles in order to, essentially, operate more like SpaceX. It is becoming increasingly difficult to pursue alternative agendas for spaceflight development, in part because components of existing policy seek to actively shut out visions that compete with the standard economic mode of thinking. Moreover, historical evidence indicates that this situation is not the result of democratic, or even relatively conscious decision-making, but rather stems from a routinized accumulation of decisions, events, and factors. Such a structure for policy-making and agenda-setting cannot guard against the encroachment of obduracy and, indeed, actually engenders it. Thus, technological development and change seems to be an autonomous force and it is no wonder that many space policy scholars see the best and only option as adaptation to this new policy direction (Cooper 2003; Genta 2014; Andrews et al. 2015) rather than advocate for more active steering.

But what can be done to avoid obduracy? Or to reduce the already existing obduracy within space development? This dissertation has analyzed each case for what contributed to obduracy. By, in turn, analyzing what else could have been done, each section has suggested several alternatives which might have reduced obduracy. By using Intelligent Trial and Error (ITE), developed by organizational and political scholars of technology (Joseph G. Morone and Woodhouse 1986; Wildavsky 1988; Woodhouse and Collingridge 1993; Woodhouse 2013), as a framework to move from problem to solution, I then generalize these suggestions which are specific to my cases to create some guidelines for a decision-making practice designed to overcome the barrier of obduracy. It is therefore pertinent that this conclusion re-examine the four mechanisms of obduracy through the lens of ITE.

Because desirable policies are more often discovered than chosen, learning is an especially important aspect of successful policy making. Accumulation acts as a substantial barrier to such trial and error learning. When policy decisions are the result of an accumulation of factors, those policies are often unintentional or haphazard. Utilizing incrementalist scholarship, especially the analytical framework of Intelligent Trial and Error (ITE), this dissertation has devised several strategies for overcoming accumulation as a barrier to learning by doing and thereby to creating more successful policies.

The first step in avoiding accumulation is agreement about accumulation, and obduracy more generally, as problems. At the most basic level, policy-makers cannot be expected to attend to the problems of obduracy if they aren't aware of them and don't agree that obduracy can cause problems.

But high levels of agreement are rare. Even if most policy-makers might agree that protecting against haphazard policies that resulted from accumulation is undesirable, they might not agree on the relative importance of this principle. Strong interests are unavoidable, and if a policy made without an eye for improvement through learning seems to coincide with the interests of a particular policy-maker, it should surprise no one if they prefer an imperfect policy under which they are a political winner over fruitful deliberation through which they might wind up a political loser. Protecting against conflicts of interest is one thing, but against holding any interests that might be met even without trial and error learning? That is a much more difficult challenge. Fortunately, trial and error learning works perfectly well when policy-makers are interested actors. It is easier to ensure that no one interest is over represented among policymakers than it is to eliminate interests altogether. Even if some of them are reticent to reexamine a policy that just accumulated without any comprehensive deliberation, they will not have enough authority to protect it if sufficient other interests are equally as authoritative.

Furthermore, when policies are the result of accumulation, it can often seem to many actors that no policy is being set at all until it actually happens. Put another way, accumulation often leads to deliberation occurring *after* a policy has already been set because policies resulting from accumulation lack any concrete opportunity to deliberate over them. Earlier and more frequent deliberation would, therefore, make it more likely to provide deliberative opportunities for policies which would otherwise have accumulated unexamined.

Accumulation can cause policy making to fall into a vicious cycle. Accumulation routinizes decision-making, which in turn makes decisions more difficult to alter in the face of errors. Routines make important decisions appear as non-decisions, and obfuscate how making small decisions regularly can add up to big and important decisions. Mechanisms to prevent falling into routines can thus help reduce the number of policies which fall prey to accumulation. One such mechanism would be to alter the position of experts in policy-making. Experts are often called on to provide the facts of the matter which policy-makers might use to make their decisions. On other occasions their expertise itself is called on to provide an informed advocate for a particular issue. However, rather than utilizing experts this way, asking them instead to act as brokers of policy alternatives (Pielke 2007) could repurpose existing incentive structures to encourage experts to expand policy options and thereby break away from routine decisions.

Policies made through accumulation also tend to favor the status quo, thereby centralizing authority among those actors and interests that already exercise significant authority. Increased centralization reduces the flexibility needed to accommodate errors which are inevitable with any policy, and also makes errors more likely in the first place. Errors are often beyond the control of even the most clever, and so decentralizing decision-making authority provides an opportunity for more scrutiny to catch errors more quickly and a better chance that some group will be incentivized to correct them.

Gradual scale-up is a potential alternative strategy to accumulation. Both start small, but while accumulated policies tend to snow ball out of control, gradual scale up increases the scale of policies in a more controlled manner. Gradually scaling up policies provides an opportunity to learn about and correct errors before they are too large to correct easily. Such a plan can offer an alternative model for thinking about how policies might grow in scale aside from accumulating.

Accumulation is, at its core, a deliberative shortcoming. Much like Winner's (1977) concept of "technological somnambulism," it prevents deliberation over the goods and ills of new technological development, as we as who experiences which. Where policy-makers sacrifice the breadth and depth of deliberation in this way, they also exclude interested social groups. This eliminates the criticism and challenge to the status quo that is necessary to resisting accumulation and therefore finding and addressing errors.

However, reducing accumulation and allowing time for learning to occur about new technological development does not ensure better policies if lock-in prevents the implementation of what is learned. Deliberative methods that prevent accumulation can thus fail if lock-in occurs first, where there is no incentive to heed deliberative outcomes or if deliberations take place too late. Looking towards the tenets of ITE can help address the barriers to learning by doing which come from lock-in.

First, deliberative exercises should be conducted early enough in the process that agenda setting is still going on and decisions are still flexible. Second, deliberative decisions should have some level of binding authority. Especially since elites are not inclined to voluntarily serve interests which may be opposed to their own.

Adding a greater variety of deliberative mechanisms and utilizing them more frequently can help to meet both of these goals. It will ensure that at least some of these mechanisms occur early enough and a diversity of methods are more likely to include a diversity of interests. For example, conducting public deliberation on decisions which seem to still be far out, and updating this deliberation by including additional public comment at important junctures.

It should always be at least possible for citizens to “vote no” on new technological trajectories, opting to cease their pursuit if learning shows the value of that trajectory to be lacking or the risks to be too high. This could be a vote, but I can’t imagine myself going to the polls for every new technological possibility. That would be onerous indeed. On the other hand, the current system of profitability is hardly sufficient. Only a very low percentage of people are required to accept a new technology in order for it be profitable. Few would accept a policy that only small percentage of people voted for, so why should they be made to accept a new technology under similar circumstances? So some other mechanism might be required to prevent pursuing a particular technological pathway. Thus, one important barrier to alleviating lock-in is that no method currently exists for rejecting a trajectory of technological development that is tied to the obduracy of that trajectory.

The first step in overcoming this barrier is the establishment of conditions under which further development is unacceptable. This might be done via any combination of various deliberative or otherwise democratic methods. What is important is that there is relatively wide acceptance about those conditions.

Once citizens establish the recognition that there are some unacceptable conditions for proceeding with any aspect of technological development, the next step is to develop a system for monitoring for those conditions. Monitoring conducted by multiple partisans, rather than "non-partisans," is likely to be most effective. Those partisans who are already in favor of alternatives would be especially watchful for errors, while the varying goals of a large number of different partisans would protect against made-up errors that benefit only one or a few sets of interests.

Of course, identifying errors is of no use if there are strong enough incentives to stay the course, as is likely if lock-in has already begun to occur. Therefore, some artificial incentives to correct errors are likely to be necessary. Something as simple as a tax on some portion of the supporting infrastructure (such as the excise tax on gas for cars) could provide a disincentive to stay the course and add resources to alleviate the costs of fixing errors. Another method might be to require proponents of new technologies to provide proof that they are unlikely to produce lock-in, as well as proof that they are addressing errors as development proceeds. This stands in stark contrast to the current system in which anyone with sufficient resources may develop new technologies mostly as they like, requiring others to prove harm.

Unchecked obduracy also exhibits path dependence, and the manner of deliberation can very much alter the pathway of technological development. Path dependence is especially likely if some interests have advantages over others in decision-making. Those interests are likely to run away with technological development, pushing it down a path that future decision-makers might not be able to alter very easily. Thus it should be uncontroversial to suggest at least that decision-makers have relatively equal information regarding at least a multiplicity of different options for any given area of technological development. However, even this somewhat simple requirement has its own barriers; namely generating multiple options from which to choose in the first place, and incentives to treat those options with relatively equal weight and resources, at least initially.

Pluralistic competition between a variety of competing interest groups of relatively equal power and authority is a system that reflects the desired plurality of development options. Thus, such a system of decision-making is likely to reduce path dependence by ensuring the exploration of multiple potential pathways.

Some suggestions that bring us closer to such a system include providing substantial advisory assistance to have-not partisans, as suggested by Woodhouse and Patton (2004). In this way, experts marshal their substantial weight to the benefit of a greater variety of interests and, therefore, pathways. We might also ask experts to not only advise but, as Pielke (2007) suggests, take on the role of honest brokers. Such honest brokers would not merely advocate for already existing options, but utilize their expertise to expand options which non-experts might not be well situated to consider. To achieve this, research support agencies would have to allocate funding differently, giving preference to less established ideas and taking more explicitly into consideration the position of the researchers themselves.

Furthermore, distribution of resources can be made more pluralistic by utilizing the same multi-partisan monitoring strategies I have already suggested elsewhere, but applied to the research of different development trajectories. For example, scientists and engineers should not be so privileged in decision-making about where to allocate research funding.

Another barrier to increased pluralism is that persistent traditions (Hommels 2005) within spaceflight may create excessive agreement without first conducing sufficient trial and error to learn what the best potential development pathway might be, and for whom. In this case, the idea that space development should be primarily for profit may become locked-in and thus reduce the potential for more pluralistic decision-making to reduce path dependency. Among other things, current laws and regulations, or lack thereof, incentivize this excessive consideration of profit making. Simply designing new laws and regulations to incentivize competing interests might be helpful.

Momentum, operating in conjunction with the other facets of obduracy, is like trying to push a large object to a desired location. Once the object gets rolling, it will be hard to stop, hard to steer, and therefore hard to ensure it actually ends up where intended. If accumulation has already begun moving it, the problem becomes even stickier, as momentum has accrued before active steering has begun. In terms of spaceflight and other technological development, if one set of interests (like privatization) sets the goals of development early on, momentum makes future steering much more difficult.

However, some momentum is difficult to avoid, so the first issue to address is how to deal with existing momentum. The first step to reducing the consequences of momentum is to begin the process with a clear policy goal. Having a clear goal from the start prevents momentum from developing in less desirable pathways prior to attempts at steering. Without a clear goal, momentum often simply favors whichever interest already has the greatest influence and power.

Of course, it is always possible that the policy goal itself also simply favors the powerful. So, as has been already emphasized, its development should be conducted pluralistically, including the maximum feasible number of interests, if obduracy is to be reduced.

Other strategies can reduce momentum as well. Momentum is dependent upon the mass of the technological system and the speed of its development. Therefore, reducing speed can reduce momentum. Development through gradual scale up necessitates a slower development, and therefore reduces momentum as well as accumulation. Large scale projects, such as NASA's RLV projects, have dominated in NASA development history and have already contributed a great deal to the momentum of privatization. Had NASA utilized strategies of gradual scale up, they might have been able to respond to errors and challenges more easily and thus not have turned to privatization strategies as quickly.

The mass of momentum, on the other hand, is primarily driven by the various innovations which attempt to solve reverse salients. Thus, incentivizing more revolutionary alternatives to these longstanding or fundamental issues might serve to keep the number of supporting artifacts, laws, experts, etc., in check. One way of enabling more revolutionary alternatives is to keep interpretive flexibility open as long as possible. Involving a greater number of interests groups in the early stages of problem deliberation will make defining the problem which needs to be solved a much more inclusive process. If combined with an appropriate and relatively equitable distribution of decision-making authority, this strategy is likely to keep interpretive flexibility of new technological developments open longer, and therefore reduce momentum.

Directly incentivizing innovation pathways which are otherwise marginal might also reduce momentum. For example, while most companies are innovating to reduce costs, NASA might fund innovations that increase reliability. Even more revolutionary, NASA might incentivize aspects of innovation that are non-technical. They might incentivize innovations that improve social mobility or international cooperation, for example. Not only would such a strategy encourage alternative innovations, they would slow down dominant innovations in favor of speeding up those that were more marginalized, thus improving opportunities for learning while also reducing momentum.

Finally, several strategies might be useful for making small adjustments in trajectory to prevent momentum from dictating developmental directions before learning has time to occur. First, targeting resources more specifically to accomplish public oriented goals can help keep development on track in the face of momentum. For example, rather than provide a certain level of indemnification for space launches in general, NASA might provide such benefits only to companies that attend to public values which they may not otherwise be incentivized to consider. Congress could also tax space development companies which don’t attend to certain public oriented values, such as fair treatment of labor or planetary protection, and use those revenues to offset costs for companies that do. Thus, even with no sum increase in costs overall, governments can incentivize public oriented behaviors if such incentives are otherwise absent. Congress has already established a so called “learning period” for private space development companies, but in reality this is just a legal promise to not enact new regulations, essentially a legal promise to avoid addressing errors! This is the opposite of a learning period. A real learning period would include: limits on the scale of development to limit the severity of consequences from errors, require scale up to be gradual to improve the likelihood of identifying errors before they become large, prioritize innovations which could be tested quickly in order to spot and fix errors quickly, and funds to ease the costs of error correction. These aspects of a learning period could be applied to areas of technological development beyond spaceflight as well.

7.2 Contributions

This dissertation contributes to the body of reconstructive scholarship (Woodhouse 2005) by focusing on maintaining future alternatives for space development. Obduracy is an analytical tool especially designed for reconstructive analysis. The direction of technological development is constructed, and thus it could be otherwise. For those analysts interested in imagining how technological development could be reconstructed in more desirable ways, obduracy is an important barrier that requires attention. In order to maximize the usefulness of the concept of obduracy, this project does more than simply describe obduracy, it treats obduracy as a barrier to better development and suggest ways in which obduracy might be avoided or overcome. Seemingly autonomous technological development may confound acting on the reconstructivist thesis that things could be otherwise. But attention to obduracy reveals the constructed nature of even the most immovable technological systems. Additionally, because obdurate systems are maintained through routinization and bureaucratic practices, they are not monolithic and can be reconstructed through new maintenance practices.

Indeed, by analyzing the barriers obduracy erects against the capacity to alter choices about the development of spaceflight, this dissertation has sought to undermine portrayals of technological innovation as occurring naturally and autonomously. “By focusing on technology as the dominant force in society – a force that progresses in inevitable ways – technocrats can justify their actions as merely being the outcome of rational, mechanical processes” (Sadowski and Selinger 2014). Ideas of technological autonomy allow for the routinization of technological development even in directions where potential harms are clear, much less those where harms are less obvious and caution all the more important. Despite what analysts like Collins and Autino (2010) suggest, no particular pathways of technological innovation and development are inevitable. Market governance is not the next natural step in spaceflight after governmental exploration. However, if obduracy continues to accumulate, it will continue to seem more and more unavoidable and impenetrable. Partisans for a pathway of spaceflight that is not monopolized by technocratic state agencies or impenetrable profit-oriented private companies are largely absent partly because the obduracy of the system gives little indication that it is possible to steer the technological system of spaceflight.

Thus the identification that obduracy hinders active, collective steering of technological development and innovation provides an important alternative to the view that such development occurs autonomously. Examining technological development using the concept of obduracy undermines naturalistic portrayals of technological change. Large technological systems can often seem autonomous, that is, like they are deterministic and unavoidable. However, my dissertation dissects how such seemingly inevitable changes are the result of obduracy. Rather than developing autonomously along a predetermined pathway, obdurate technological systems accumulated according to decisions made by proximate decision makers and social factors.

If technologies do not develop autonomously, then the direction of their development is a political decision. This dissertation therefore treats technological development as a political matter. Moral values guide the direction of innovation because innovations occur in response to problems. Much of technology studies charts a similar history. Many scholars have shown how social decisions and interests are made durable in technological systems. This is part of the social constructivist thesis that "things could have been otherwise." However, the field of technology studies retains room for more scholarship on how that process of making the social durable prevents citizens from actually making alterations. By addressing obduracy, this dissertation addresses a significant barrier to this reconstructivist goal. In much the same way that Winner (1977), shifted analysis from technologies as neutral towards technologies acting as legislation, the obdurate technologies in this dissertation may act something like a constitution. Once established it is very hard to undo or redo.

Technological development moves humanity towards a vision of the future, and each innovation overcomes one small barrier to achieving that vision. There is profound disagreement, in general, over which moral values should guide development towards which visions of the future. But I need not make predictions. Instead, I simply claim that, given the political nature of technological development, space development included, obduracy not only makes learning by doing more difficult, but locks in those politics without the chance for potential opponents to at least have a say, and for future generations to change their minds. Democratic governance need not be opposed to the use of market mechanisms to meet political and technological goals, but it does require that obduracy be reduced in order to ensure that citizens continue to have a say in the technological world in which they live.

This dissertation combines the approach to partisan analysis suggested by Lindblom (1986) with the honest broker approach suggested by Pielke (2007). I do this by suggesting methods for maintaining policy alternatives, thus expanding the potential breadth of policies under discussion. I have articulated some alternative pathways to the current trajectory of space development in order to demonstrate the ways in which current understandings of technological innovation have constrained the possibilities for spaceflight. I have not promoted one of these over others, instead choosing to endorse caution against the obduracy that would lock-out these alternatives. I also suggest that other scholars might utilize a similar model. By attending to conflicts over which values should be expressed in technological development and exposing a variety of potential pathways, scholars can much more easily enable learning. Sometimes, being a partisan may mean advocating for the expansion of possible policies rather than just advocating for an existing choice.

Several scholars have addressed issues such as obduracy (Hommels 2005) and inflexibility (Collingridge 1992) in the past. However, no work to my knowledge utilizes these bodies of scholarship in conjunction. Hommels describes obduracy primarily as resistance to change. I expand on this conception by accounting for the ways in which rapid changes can still occur while retaining a static *trajectory* of development. Rapid innovations can increase momentum, or lock-in some interests at the expense of others. Instead, this dissertation describes obduracy as a resistance to steering rather than to change. This dissertation extends Collingridge's analysis of inflexibility to address systemic causes of inflexibility and therefore barriers to increased flexibility. Inflexibility contributes to obduracy, but is more suited for analysis of individual artifacts or sets of artifacts, while obduracy is more suited to analyze the technosocial system in which those artifacts are a part. Furthermore, obduracy extends both frameworks to help define relative degrees and variations of obduracy. In other words, obduracy is not merely one end of a binary opposite malleability. Technosocial systems can have varying degrees of each facet presented in this dissertation. Not only, then, are there varying degrees of obduracy, but potentially varying kinds as well, depending on which facets contribute the most.

Additionally, the facets such as accumulation, lock-in, path dependency, and momentum have all been put to use by various scholars to make their own significant contributions to STS. However, much can be gained by putting such concepts next to one another in conversation. This dissertation does just this work. By applying each of these concepts in turn to the case of the privatization of spaceflight, I have built up a new framework with which to analyze the development of new technological systems. These concepts together become facets of obduracy, which serves as an analytical framework focused on barriers to more intelligent technological development. It is useful descriptively, but also prescriptively and enables analysis which is more easily directed towards useful application by partisans.

This dissertation represents a much needed update to incrementalist literature, especially within STS. Major and frequent updates to incrementalism, trial and error learning, and related areas of scholarship have been somewhat stagnant for the past 15 years. Excepting one recent book publication in this area (Dotson 2017), the most recent bout of scholarship is between five and 20 years old (Genus 2000; Woodhouse 2013). As such, this dissertation seeks to tackle the application of many of the principles addressed in these previous works. Being both incrementalist and reconstructivist, the principles of ITE are well suited for their application in thoughtfully partisan scholarship such as conducted in this manuscript. Thus it is my intention that this dissertation both dutifully seek to apply the principles of ITE and other frameworks for better policy decisions to the reduction of obduracy in an important area of emergent technological development. Furthermore, this dissertation should serve as a basis or model for future applications of these same frameworks.

Such scholarly contributions are not the only ones I have intended to make with this dissertation. I have intended to produce an analysis that is not only useful for STS or policy analysts, but also for those space enthusiasts who are not quite satisfied with the solution of market governance, or with the definition of whatever problem that solution is supposed to solve. I have, of course, produced nothing on the scope of a guide to better space policy. However, I hope I have produced a dissertation that at least some like-minded space enthusiasts may find useful in articulating their visions for spaceflight or their problems with spaceflight as it has been so far conceived. I have tried to maintain a focus on spaceflight and increase accessibility by grounding the theoretical contributions in vignettes that make up the body of the dissertation. In addition, the dissertation attempts to maintain a future orientation in order to prevent the possibility of reading like an esoteric history and to instead provide tools for moving forward and engaging those less interested in the academic contribution and more interested in its practical usefulness. Finally, I suspect that the number of space enthusiasts is far greater than simply the number of people who want either a state or a market governed space program. Both I and some of my informants, at least, feel as if we must choose between two undesirable options. The alternative for many space enthusiasts may be to distance themselves from the field. Thus I have created a text that is designed to reach out to such partisans and provide them an avenue for engagement. While some STS scholars may be disinterested in the details of spaceflight provided, I hope that by doing so I have made this book accessible to an audience outside of STS.

7.3 Further Scholarship

This dissertation has demonstrated that obduracy presents a barrier to more intelligent development of outer space, but obduracy may have important applications to other areas of study as well. Hommels (2005) has already provided analysis of obduracy and urban design, as she describes her observations of what seems to contribute to obduracy in this domain. As this dissertation focuses more heavily on the consequences of obduracy, and aspects of its formation most suitable for intervention, continuing to utilize obduracy in this way could help to alleviate this general normative deficit present throughout much of STS. This is especially true for emerging technologies. Solar roadways and self-driving cars, for example, are situated to potentially make serious changes to existing transportation infrastructure. But while these technologies have the potential for increasing roadway efficiency and safety and decrease dependence on fossil fuels, they may contribute to the obduracy of other technological systems with less desirable outcomes. Would self-driving cars make more dense urban development more difficult and contribute to the social isolation of current suburban housing designs? Would solar roadways perpetuate the exploitative labor conditions or pollution caused by rare-earth element mining? Obduracy could be a tool for psycocultural goods as well as technological ones. For example, obduracy may be a strong analytical tool for scholars looking to overcome barriers to greener or more communitarian urban design (Dotson 2016). It is my hope that obduracy proves to be useful for a variety of different cases in other reconstructive scholarship. Scholarly and public attention paid to mechanisms of obduracy creation could help STS scholars to analyze emerging technologies in such a way as to be useful for partisans with a stake in its development and therefore have a greater impact in shaping future technological development for the better. Such attention could not only alleviate the dearth of normative scholarship, but also the lack of scholarship addressing important contemporary technological developments.

The reconstructivist framework of Intelligent Trial and Error (ITE) was originally developed to analyze risky technologies and organizational mistakes (Joseph G. Morone and Woodhouse 1986; Woodhouse and Collingridge 1993; Woodhouse 2013). Although this dissertation does not systematically apply ITE to analyze obduracy, many of the discussed alternatives and potential aids for minimizing the facets of obduracy take advantage of the elements of ITE to provide an analytical foundation. Thus, this dissertation prepares the groundwork for extending ITE to obduracy by recognizing that ITE may be analytically useful beyond its current application for averting technological and organizational errors. Indeed, while this research addresses generally what might be required to mitigate against or reduce obduracy, ITE presents a more concrete analytical strategy for heading off obduracy in future technologies. The primary error of obdurate technological development is the loss of capacity to (democratically) decide about the future of technological development. This is a very different, and much bigger, type of error than the unintended consequences and financial repercussions so far discussed by scholars such as Woodhouse (1988), Collingridge (1992) and Genus (2000). Any future scholarship that applies obduracy to the analysis of emerging technologies would benefit from this extension of the ITE framework to thus use it to tackle such large scale and encompassing errors.

While reconstructivists may gain a valuable tool in obduracy, the emerging technologies, both physical and organizational, of spaceflight and space development are important targets of study in their own right. While this dissertation introduces obduracy as a barrier to many alternatives, it does not thoroughly explore any specific alternatives in depth. For example, Pop (2000) argues that appropriation of outer space resources is illegal under current law. In his book (Pop 2008) he details the construction of the sociotechnical institutions that afford the development of outer space despite the legal barriers. Yet many questions remain. What are alternative legal frameworks? Who do different possible legal frameworks benefit? How could it and *should* it be otherwise, and what are the barriers to achieving such alternative frameworks for space law? As private companies begin to send people into space, or to develop the resources there, how is employment outside the bounds of Earth to be regulated? Astronauts currently work hours that would violate labor laws on Earth, and do so in one of the most hostile environments imaginable. Is this precedent to extend to private employees? How could labor in space be better constructed? Numerous important areas of analysis about spaceflight still exist, and those who want more sustainable, democratic, or other progressive futures in space would do well to attend to them.

Beyond the subject of spaceflight, the themes of technological obduracy, market governance, and democracy that have been discussed have more thorough theoretical connections than could be explored in this dissertation. Market forces governing technological development present particular sorts of obduracy because decision-making by corporate executives sometimes intentionally seeks to freeze out competitors, protect against public “interference,” and lock-in technological and other advantages (Lindblom 1982, 2001). While the market orientation in private spaceflight has enhanced obduracy, both markets and democracy offer coordination through mutual adjustment (Lindblom 1965) and promise some kinds of learning by doing. This complicates broader statements about the relationship between markets and obduracy than are made in this dissertation. That markets can limit the range of choices available to citizens beyond mere consumer selection, however, is a constraint that contributes to obduracy. The situation is clearly complicated. Democratic institutions acting as economic agents rather than an outside power may increase the *range* of choice and affordability of technological pathways which could be more appealing to more people. For instance, Woodhouse (2012) describes a system in which wholesalers, those organizations which purchase from manufacturers to distribute to retailers, were induced to be more publicly minded through a democratic system of representation rather than the status quo in which wholesalers are usually private companies. Regardless of one’s position on this particular suggestion, more scholarship of this sort is important to realize better synergy between market and democratic institutions and mechanisms. The idea that governments act on the economy from the outside is, itself, obdurate and may stunt creative visions and action towards political-economic arrangements that better serve some or many stakeholders. Better outcomes could be systematically available by blurring this boundary.

At the beginning of this book I introduced a choice that, in the broadest of terms, every technological society must make: is technological development to proceed blindly by plunging ahead or is to proceed intelligently, evaluating technologies as we go and mitigating the harms of errors experienced along the way? I have advocated for the latter and, I hope, provided an analysis that eases some of the immense difficulties in actualizing that seemingly obvious answer. At the crux of my analysis has been one concept: that obduracy, the difficulty in being able to alter a decision about technological development in response to errors, is itself a major barrier in actualizing more intelligent steering of technological development. By examining the privatization of space development, an emerging area of technological development that promises consequential outcomes, I have shown the potential dangers of allowing obduracy to accumulate. However, more than merely identifying those factors which have led to developing spaceflight obdurately, I have outlined some suggestions for ways in which obduracy in spaceflight and beyond may be reduced. In performing this analysis, I have been much more than a describer of this phenomenon, I have been a partisan. The problems with obduracy are more than technical. Obduracy reduces the prospects for citizens to have a say in their own technological futures. In so far as I, or anyone else, believes in such democratic steering, I have intended for this book, most of all, to be a small piece in the effort to make our technological society more democratic.

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