The Timing of Resource Development and Sustainable Competitive Advantage

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Abstract

We deepen and extend resource-level theorizing about sustainable competitive advantage by developing a formal model of resource development in competitive markets. Our model incorporates three important barriers to imitation: time compression diseconomies, causal ambiguity and the magnitude of fixed investments. Time compression diseconomies are derived from a micro-model of resource development with diminishing returns to effort. We characterize two dimensions of sustainability: whether a resource is imitable and how long imitation takes. We identify conditions under which competitive advantage does not lead to superior performance and show that an imitator can sometimes benefit from increases in causal ambiguity. Despite recent criticisms, we reaffirm the usefulness of a resource-level of analysis, especially when the focus is on resources developed through internal projects with identifiable stopping times.

Key words: barriers to imitation, formal foundations of strategy, project management

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1. Introduction

At the core of the field of business strategy is the notion of sustainable competitive advantage (Porter, 1985). The leading approach to sustainability among strategy researchers is to identify hard to imitate resources that underlie a firm’s competitive advantage (Dierickx and Cool, 1989; Barney, 1991). Examples of resource-based advantages include a firm that has lower costs than competitors due to a proprietary production process or a firm that generates a superior willingness-to-pay due to an advanced product design. Competitive advantage is sustainable to the extent that it persists over time, with the strategy literature particularly concerned with the threat of competitors neutralizing an advantage through imitation of the underlying resources.

1.1. Crisis in the RBV

Although the resource-based view (RBV) retains a central position in strategy research, there is concern that it is no longer serving as an effective engine for moving the field forward. The core assertion of the RBV is that superior performance can be reduced to the possession of valuable, rare and hard to imitate resources. This approach to strategy was originally developed using verbal arguments grounded in economic reasoning (see Peteraf, 1993, for a synthesis). A prominent attack on the received theory is Priem and Butler (2001) who argue that the link between valuable, rare and inimitable resources and superior performance is tautological. Another of their critiques is that there is insufficient attention to how resources actually create value in competitive product markets. Other critiques are possible as well. The core propositions of the RBV are very broad, but they lack depth and specificity, especially in terms of the strategy dynamics which they consider. For example, analysis tends to start with initial resource heterogeneity and hence the dynamic linkages between imitation processes and initial resource development tend not to be studied.

Despite increasing concerns and dissatisfaction with the RBV, no other perspective has effectively challenged its centrality to the field. Resources as a level of analysis distinct from firms and industries is proving to have great staying power. In particular, researchers in
strategy continue to use the RBV extensively to frame and motivate their empirical work. We support the continued use of a resource level of analysis for the study of sustainable competitive advantage. Our objective is to deepen the theoretical foundations of the RBV in ways that address recent criticisms. Specifically, we develop a dynamic model of resource development by firms competing in a market and then use it to elucidate and extend the received verbal theory.

1.2. The Phenomena and Our Model

For many resources, the time required for resource development is extensive (Ghemewat, 1991). The team working on the development of Intel’s 386 microprocessor took 48 months ("Intel Corporation: 1968-2003," HBS case study). There is extensive data on time-to-build for new plants (Koeva, 2000; Pacheco-de-Almeida et al., 2005), which can be as low as 13 months for simple commodity products such as rubber and more than double for more technologically advanced products such as transport equipment. The development of the Airbus A380 took five years (Esty and Ghemawat, 2002). Several influential management books emphasize the timing dimension of strategy including the work of Fine (1998) on industry clockspeed and before that the work of Stalk (1988) on time-based competition. Clark (1989) estimates that each day of delay in introducing a new model represents a $1 million loss in profits for a $10,000 car. Timing matters.

Our formal model starts with the forgone revenues due to delays in resource development. We combine this with a micro-model of the resource development process, which has the following key features. Firms develop resources via discrete development projects that vary in their complexity (Simon, 1996; Rivkin and Siggelkow, 2002). Spillovers from firms that have already developed the resource (Mansfield et al., 1981) can reduce complexity. Spillovers are inversely related to causal ambiguity (Rumelt, 1984; Reed and DeFillippi, 1990), which is an important barrier to imitation that reflects the extent to which competitors do not understand the sources of a firm’s competitive advantage. Firms exert effort over time towards resource development, with effort at a point in time subject to diminishing returns.
A fundamental property of our resource development process is time compression diseconomies (Dierickx and Cool, 1989) such that the faster a firm seeks to develop a resource the greater the development costs.\textsuperscript{1} Hence, when firms choose the timing of resource development they face a tradeoff between the forgone earnings from delayed deployment of the resource and the increased costs from time compression diseconomies. In making this tradeoff we assume that firms maximize the present value of the revenues from deploying the resource in the market net of the development costs. The use of net present value (NPV) calculations in a continuous time model of investment projects allows us to narrow the gap between research in strategy and finance.

We focus on a duopoly setting where there is a leader and a follower. In the base model, the leader already has the resource and the follower can seek to imitate the leader’s resource, mirroring the standard RBV approach to sustainability. In an important extension, we add initial resource development by leader. A second extension allows the leader to license some of its knowledge about resource development to the follower.

1.3. Questions and Contributions

We address several fundamental questions in competitive strategy. What determines the sustainability of competitive advantages based on internally developed resources? Within our model, we can derive a precise answer. What is the relationship between competitive advantage and relative performance? These are distinct constructs in our model. Finally, we consider firm IP strategy: under what conditions should a leader license its knowledge about the resource development process to a firm seeking to imitate its resources? What is the optimal level of spillovers for an imitating and an imitated firm?

Our paper is part of an emerging literature that is developing formal theoretical foundations for strategy. The closest prior contributions are Makadok and Barney (2001) and Makadok (2001), who are also developing formal foundations to the RBV. While their work seeks to

\textsuperscript{1}Mansfield (1971) empirically estimates the extent of time compression diseconomies. He finds that a one percent reduction in project duration leads to a 1.75 percent increase in development costs. These estimates imply that a two week compression of Intel’s 386 development project would have resulted in a $3.5 million increase in development costs.
formalize the concept of strategic factor markets from Barney (1986), our focus is on internally developed resources as emphasized by Dierickx and Cool (1989). Another formal study that takes a resource-level of analysis is Adner and Zemsky (2006), which considers how resource rents erode over time due to exogenous forces operating in a firm’s environment. We offer the first formal treatment of resource development and sustainable competitive advantage. Our theory is more dynamic than prior foundational work in strategy. By working with a continuous time model, we are able to consider time as an explicit part of the firm’s competitive strategy. By sequencing the resource development activities of the leader and follower, we incorporate the effect of the follower’s optimal timing on the leader’s resource strategy.

In terms of sustainability, we first consider whether or not the leader’s resource is inimicable. In our theory, an inimicable resource is one that is uneconomical for the follower to develop (rather than literally being impossible to develop), which occurs when the fixed cost of developing the resource exceeds the benefits of possessing it. We characterize a dynamic version of this basic mechanism where both the level of the fixed costs and the present value of the benefits are endogenously determined by the follower’s choice of development time. For resources that are imitated, sustainability depends on how long the follower takes to develop the resource. We derive an explicit expression for the optimal development time of the follower.

We show that sustainability is increasing in both the complexity of resource development and the cost of capital and decreasing in the level of spillovers. Interestingly, the extent of diminishing returns has a non-monotonic effect on sustainability. While some diminishing returns are required for time compression diseconomies, we find that increases in the extent of diminishing returns need not imply greater time compression diseconomies and greater sustainability.

Rumelt (2003) points out that competitive advantage is not consistently defined in the strategy literature and he suggests that settling on a definition may be sufficiently difficult that the field should consider dropping the term! Our theory offers one approach to making

\footnote{Another branch of the formal literature starting with Brandenburger and Stuart (1996) is deeply foundational and seeks to use cooperative game theory to study the fundamental relationship between the value creation possibilities by sets of participants in an industry and each party’s ability to capture value (Lippman and Rumelt, 2003; McDonald and Ryall, 2004).}

\footnote{The work of Casadesus-Masanell and Ghemawat (forthcoming) and Casadesus-Masanell and Yoffie (2005) is noteworthy in introducing dynamic modeling into the strategy literature.}
precise the notion of competitive advantage. We say that a firm has a competitive advantage over another firm when resource asymmetries at a point in time give it superior cash flows. Competitive advantage, as a concept that applies at a point in time, can then be distinguished from intertemporal performance measures based on NPV calculations. The cost of developing the underlying resources, which are incurred prior to the increase in revenues from the competitive advantage, must be factored into performance comparisons. While the leader necessarily has higher performance for inimitable resources, we show that for imitable resources the follower has superior performance for sufficient spillovers or, equivalently, if causal ambiguity is sufficiently low.

Causal ambiguity, as a barrier to imitation, is generally taken to be good for leaders and bad for followers. This implies that followers should seek to reduce causal ambiguity by collocating with leaders to facilitate interorganizational learning or by taking actions to increase absorptive capacity (Cohen and Levinthal, 1990). We confirm that high levels of causal ambiguity are beneficial for the leader due to enhanced sustainability. Despite the fact that causal ambiguity delays imitation and raises development costs for the follower, we show that increasing causal ambiguity (and hence decreasing spillovers) can actually increase the performance of followers. This result, which is counter to the received wisdom in strategy, arises because of the negative impact on the leader’s incentive to compress time in its initial resource development. Faster imitation, means slower development by the leader which is harmful to the follower. Finally, we find that licensing should be more prevalent the easier it is to develop the resource (i.e., the lower the causal ambiguity and the complexity).

The paper proceeds as follows. Section 2 specifies the model. Section 3 derives from first principles the extent of time compression diseconomies. Section 4 characterizes the sustainability of the leader’s competitive advantage. Section 5 characterizes the optimal development budget of the follower and derives comparative statics on firm performance. Section 6 extends the model to allow for licensing prior to the follower’s resource development. Section 7 extends the model to include initial resource development by the leader. Section 8 concludes. Proofs are in the Appendix.
2. The Model

There are two firms competing in an output market. We label the firms \( L \) for leader and \( F \) for follower. The leader has a valuable resource (e.g., an offshore call center that reduces costs or a process for incorporating advanced safety features into products for which consumers are willing to pay a premium). While the leader is assumed to already have the resource, the follower does not. The follower can imitate the leader and develop its own version of the resource. (In section 7, we extend the model to include initial resource development by the leader.) When the leader has the resource and the follower does not, we say that the leader has a competitive advantage; otherwise the firms are assumed to be identical and there is competitive parity.

The model is in continuous time denoted by \( t \geq 0 \). Firms incur costs and receive revenues over time and they seek to maximize the net present value of their cash flows for a common discount rate \( r > 0 \), which reflects the cost of capital for the firms. We denote by \( T_F \) the time at which the follower develops the resource. If the follower does not develop the resource, we set \( T_F = \infty \).

2.1. Product Market Competition

Firm revenues from the product market depend on whether or not the follower has the resource. From \( t = 0 \) until \( t = T_F \), the leader has a competitive advantage because it alone has the resource and we denote its flow of revenues by \( \pi_{ca} \). During the same interval \( 0 \) to \( T_F \) the follower has a competitive disadvantage and its revenues are denoted \( \pi_{cd} \), which we assume satisfies \( 0 \leq \pi_{cd} < \pi_{ca} \). From time \( T_F \) there is competitive parity because both firms have the resource and both firms have the same revenue flow \( \pi_{cp} \), which we assume satisfies \( \pi_{cd} < \pi_{cp} \leq \pi_{ca} \).  

The present value of the leader’s revenues are then

\[
R_L(T_F) = \int_0^{T_F} \pi_{ca} e^{-rt} dt + \int_{T_F}^{\infty} \pi_{cp} e^{-rt} dt,
\]

\[\text{4} \text{Our approach to modeling profit flows over time is used in the industrial organization literatures on new technology adoption (e.g., Reinganum, 1981).} \]
while those of the follower are

$$R_F(T_F) = \int_0^{T_F} \pi_{cd} e^{-rt} dt + \int_{T_F}^{\infty} \pi_{cp} e^{-rt} dt.$$  

It is useful to define $\Delta_F = \pi_{cp} - \pi_{cd} > 0$, which is the increase in cash flows for the follower when it completes resource development.

### 2.2. Resource Development

The resource development process has three key attributes: the inherent complexity, the degree of spillovers from the leader to the follower, and the extent of diminishing returns to effort. The complexity of resource development increases in the number of required steps and the interconnections among them. For example, developing a new product might require steps such as market research, product design, prototype testing, plant construction or modification, and signing up distributors with significant dependencies among them. Such a project would in be more complex, for example, than introducing a process improvement in order fulfillment. We parameterize the complexity of the resource development process by $K > 0$.

The follower can potentially reduce the complexity of resource development due to spillovers from the leader (Mansfield et al., 1981). For example, the follower may learn about resource development by reverse engineering the leader’s product, hiring its engineers and talking to its suppliers. We parameterize spillovers by $s \in [0, 1)$ and assume that the level of complexity faced by the follower is $(1-s)K$. The parameter $s$ can be linked with two important constructs in the strategy literature. The extent to which the follower learns from the leader decreases in the extent of causal ambiguity and increases in the absorptive capacity of the follower.\(^5\)

Our model of the resource development process builds on Lucas (1971).\(^6\) The follower exerts effort at time $t$ given by $z_t \geq 0$. There are diminishing returns to effort so that the resource development project progresses at a rate $(z_t)^\alpha$ for some $\alpha \in (0, 1)$. For a given

\(^5\)Thus, we allow for complexity and causal ambiguity to be potentially independent constructs in our theory. This is supported by Ryall (2005) who formally models the inference problem of a follower.

\(^6\)We thank Francisco Ruiz-Aliseda for suggesting that we use this under exploited paper.
development time $T_F$, an effort profile $z_t$ must satisfy the following feasibility condition

$$\int_0^{T_F} (z_t)^\alpha dt = (1 - s)K,$$

which assures that all steps are done by the completion date.

The flow of costs associated with resource development are proportional to the effort, $c_t = bz_t$. Without loss of generality, we take $b = 1$. The discounted cost of resource development is then $\int_0^{T_F} z_t e^{-rt} dt$. We denote a cost minimizing effort profile for a given $T_F$ by $z_t^*(T_F)$, which is characterized in the next section. The present value of the follower’s resource development costs are then

$$C(T_F) = \int_0^{T_F} z_t^*(T_F) e^{-rt} dt.$$

For the case where the follower does not develop the resource, we set $C(\infty) = 0$.

When $\alpha = 1/2$ the cost of progress is quadratic.$^7$ The model is more tractable in this case and we make this simplifying assumption when extending the model in sections 6 and 7.

The follower seeks to maximize the net present value of its cash flows as given by $\Pi_F(T_F) = R_F(T_F) - C(T_F)$.

### 3. Time Compression Diseconomies

We begin the analysis by characterizing the relationship between the timing and the cost of resource development. Formally, this involves solving for the cost function $C(T_F)$. Not surprisingly, the cost function depends on the parameters of the development process ($K$, $s$ and $\alpha$) and, as we will show, on the cost of capital $r$.

The function $C(T_F)$ is defined for the cost minimizing effort profile $z_t^*(T_F)$, which balances the following tradeoff. Diminishing returns to effort ($\alpha < 1$) calls for spreading effort uniformly over time. On the other hand, discounting calls for delaying effort. There exist closed-form expressions for the optimal effort profile and for the resulting cost function.

$^7$If $k_t = (z_t)^\alpha$ is the rate of progress made on the project at time $t$, then when $\alpha = 1/2$ we have that $c_t = z_t = k_t^2$ and the cost of progress is a quadratic function of the rate of progress.
Proposition 3.1. For a given project completion time $T_F < \infty$, the cost minimizing effort profile is
\[
z^*_t(T_F) = e^{rt/(1-\alpha)} \left( \frac{\alpha}{1 - \alpha \ e^{rt_F/(1-\alpha)} - 1} \right)^{1/\alpha}
\]
and the resulting cost function is
\[
C(T_F) = (1 - s)^{1/\alpha} K^{1/\alpha} \left( \frac{\alpha}{1 - \alpha \ e^{rt_F/(1-\alpha)} - 1} \right)^{\frac{1-\alpha}{\alpha}}.
\]

For the case of a quadratic cost of progress ($\alpha = 1/2$), we have the simpler expressions
\[
z^*_t(T_F) = e^{2rt} \left( \frac{r(1-s)K}{e^{rt_F} - 1} \right)^2,
\]
\[
C(T_F) = (1 - s)^2 K^2 \frac{r}{e^{rt_F} - 1}.
\]

The optimal level of effort increases over time due to discounting and decreases in the total development time ($T_F$). Figure 3.1 illustrates the relationship between the development time and development costs for two levels of spillovers. The resource development process exhibits time compression diseconomies: the faster the firm seeks to develop the resource, the greater the cost. Formally, we have that $C'(T_F) < 0$. There are two sources of the negative relationship between time and costs. First, longer development times reduce the level of effort in each period, which lowers costs due to the diminishing returns to effort. Second, longer development times shift effort into the future, which lowers the present value of effort costs.\footnote{There are time compression diseconomies even without the second effect. The present value of development costs at the time of completion, $C(T_F)e^{rt_F}$, is still decreasing in $T_F$.}

The functional form of $C(T_F)$ has two convenient properties. First, as the development time goes to zero, costs become arbitrarily large. Consequently, there cannot be a corner solution where resource development is instantaneous. Second, both the cost and the revenue functions depend on $T_F$ through an exponential form. This allows us to derive closed form expressions for the optimal development time and firm profits.\footnote{In an early version of this paper, we did not have an explicit resource development process and we used the
Figure 3.1: Time compression diseconomies when $K = 4$, $r = 0.1$, $\alpha = 0.5$ and $s = 0$ versus $s = 0.5$.

The existence of time compression diseconomies is an essential driver of the results in the paper. The concept was first related to sustainability by Dierickx and Cool (1989) in their work on resource accumulation. Graves (1989), who reviews the theoretical and empirical literature on the time-cost tradeoff in development projects, identifies several broad sources of time compression diseconomies. One is diminishing returns to effort. As he states, “a complex R&D task which could be performed by one person in 24 months could not be performed in one month by 24 persons” (p. 2). One way to shorten development projects is to shift tasks from sequential to parallel execution. However, this can result in costly mistakes and rework when there are interdependencies among tasks (since information is lost when tasks are performed concurrently). These sources of time compression diseconomies are reflected in our modeling of the resource development process based on complexity ($K$) and diminishing returns ($\alpha$). The importance of diminishing returns is emphasized in Cool et al. (2002) who state “Time compression diseconomies reflect the ‘law of diminishing returns’ when one input, viz. time, is held constant.” (p. 60). Our formalization makes explicit the links between complexity and cost function $C(T) = C_0 + \phi K e^{-T/\phi}$. The drawbacks to such an approach are the lack of micro foundations, independence from the cost of capital, and the need to restrict the parameters to assure that $T^* > 0$. 

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diminishing returns on the one hand and time compression and sustainability on the other.

There are parallels between our model of resource development and the IO literature on new technology adoption (Reinganum, 1981; see Hoppe, 2002, for a survey). As in our model, the new technology adoption literature assumes that there is a time-cost tradeoff in that the cost of adoption is assumed to fall over time. Moreover, it assumes that there is an opportunity cost to delay because of reduced revenue flows from the market. However, the process that leads to falling costs is taken as entirely exogenous and as common to all firms in that literature. Consequently, the cost function $C(T)$ is exogenously given and the case where a leader develops/adopts the resource and the follower seeks to imitate, which is the focus of our theory, is not been considered.

4. Resource Imitation and Sustainability

The sustainability of the leader’s competitive advantage depends on the resource development strategy of the follower. One possibility is that it is uneconomical for the follower to develop the resource, which would make the resource inimitable. We derive a precise condition for the resources in our model to be inimitable. If the resource is imitable, then the leader’s advantage is only sustained for a limited period of time, the length of which is determined by how long the follower takes to develop the resource. We derive an expression for the follower’s optimal development time.

For the follower, the size of the investment in resource development is given by $C(T_F)$. According to standard finance theory, investment decisions should be driven by net present value calculations. The present value of the investment returns in our model is $R_F(T_F) - R_F(\infty)$, which is the present value of revenue flows with the resource less the present value of revenues without the resource. The present value net of the investment cost is then: $R_F(T_F) - R_F(\infty) - C(T_F)$. In our theory, both the returns to the investment and the investment cost are endogenously determined by the follower’s choice of development time.\textsuperscript{10}

\textsuperscript{10}We can rewrite the net present value $R_F(T_F) - R_F(\infty) - C(T_F)$ as $\Pi_F(T_F) - \Pi_F(\infty)$. Our assumption that the follower maximizes $\Pi_F(T_F)$ is then equivalent to assuming that the follower invests based on NPV calculations. NPV calculations govern both the decision as to whether or not to invest in resource development.
Figure 4.1: The effect of development time on the net present value of resource development for $K = 4$, $r = 0.1$, $\alpha = 0.5$, $\pi_{cd} = 3$ and $\pi_{cp} = 3.1$ (left panel) and $\pi_{cp} = 4$ (right panel).

Due to time compression diseconomies, the follower benefits from slowing down resource development, $C'(T_F) < 0$. However, there is a cost to the delay. The follower loses the increase in cash flows $\Delta_F = \pi_{cp} - \pi_{cd}$ that comes from deploying the resource in the market (in particular, $R_F(T_F) - R_F(\infty) = \Delta_F/(re^{rT_F})$). Figure 4.1 shows how the follower’s NPV from resource development depends on $T_F$ for two different values of $\Delta_F$ and is discussed below.

4.1. Inimitable Resources

In the left panel of Figure 4.1, the cost function always exceeds the returns to developing the resource and investing in resource development yields a negative NPV for all finite times. In such a case, it is optimal for the follower not to develop the resource ($T_F^* = \infty$). The barriers to imitation are sufficient to deter resource imitation by the follower and the competitive advantage of the leader is sustainable. We now identify the general condition for the resource to be inimitable.

as well as the optimal size/timing of any investment.
Proposition 4.1. The resource is inimitable if and only if

$$\Delta_F \leq (r(1-s)K)^{1/\alpha} \left( \frac{\alpha}{1-\alpha} \right)^{1-\alpha},$$  \hspace{1cm} \text{(IN)}$$

which assures that the NPV of an investment in resource development is negative for any finite development time. Inimitability is associated with larger values of $K$ and $r$ and smaller values of $\Delta_F$ and $s$. The effect of $\alpha$ is non monotonic, with the RHS of (IN) at first increasing and then decreasing in $\alpha$.

The expression on the right hand side of condition (IN) is a measure of the economic barriers to imitation associated with the resource. For the resource to be inimitable, these barriers must be greater than the returns to resource development as given by $\Delta_F$. As expected, the barriers to imitation are increasing in the complexity ($K$) of resource development and decreasing in spillovers ($s$), which in turn depends on the degree of causal ambiguity maintained by the leader and the absorptive capacity of the follower. The cost of capital $r$ increases the barriers to imitation in two ways. By pressuring the follower to delay effort, it magnifies the effect of diminishing returns. Second, an increase in $r$ increases the present value of costs relative to the present value of revenues because costs are incurred earlier. In a static analysis, resources are inimitable when the cost of acquisition exceeds the returns to deploying the resource in the market. We have derived a dynamic version of this mechanism where both the cost of resource acquisition and the payoff to deployment are endogenously determined by the time taken for resource development.

The barriers to imitation depend on the extent to which there are diminishing returns to effort at a point in time. In particular, $1/\alpha$ determines the extent to which there is a convex effect of $r$, $(1-s)$ and $K$ on the barriers to imitation. The direct effect of diminishing returns on the barriers to imitation is more complex. The RHS of (IN) is non monotonic in $\alpha$. At first increases in $\alpha$ (starting from $\alpha = 0$) decrease the barriers to imitation and then for $\alpha$ sufficiently high, they raise the barriers to imitation.
4.2. Sustainability with Imitable Resources

When inequality (IN) is not satisfied, resource development is profitable. Specifically, for $T_F$ above a threshold the cost curve falls below the returns as illustrated in the right panel of Figure 4.1. In this case, there is a unique $T^*_F$ that maximizes the NPV from resource development, which is given by the difference between the two curves. The optimal development time satisfies the first order condition $R'(T^*_F) = C'(T^*_F)$, which has a closed form expression.

**Proposition 4.2.** Suppose that (IN) is not satisfied. The sustainability of the leader’s competitive advantage is given by the optimal development time of the follower, which is

$$T^*_F = -\frac{1}{r} \ln \left( 1 - \frac{r(1-s)K}{\Delta^\alpha_F ((1-\alpha)/\alpha)^{1-\alpha}} \right)^{1-\alpha}$$

(4.1)

The optimal development time is decreasing in $\Delta_F$ and $s$, increasing in $K$ and $r$, and non monotonic in $\alpha$.

For the case of a quadratic cost of progress ($\alpha = 1/2$), we get the simpler expression

$$T^*_F = -\frac{1}{r} \ln \left( 1 - \frac{r(1-s)K}{\sqrt{\Delta_F}} \right).$$

(4.2)

The greater is $\Delta_F$ the more the follower is motivated to compress time and the less sustainable is the leader’s competitive advantage. The greater the complexity of resource development after spillovers, as given by $(1-s)K$, the longer the follower takes to imitate the leader. Finally, the greater the cost of capital the less profitable the opportunity and the less motivated is the follower to compress time. The effect of $\alpha$ is again ambiguous.

4.3. Discussion

There are two dimensions to sustainability: whether or not the resource is imitated and if it is, how long imitation takes. Along both dimensions, we find that sustainability is increasing in complexity and in the cost of capital and decreasing in spillovers and in the follower’s returns to resource acquisition. Interestingly, on neither dimension of sustainability do we find...
consistent results for the effect of the diminishing returns to effort. Figure 4.2 contrasts the
effect of $K$ and $\alpha$ on sustainability. For low levels of complexity the resource is imitable with
the imitation time increasing and convex in $K$. There is a threshold at which the imitation
time goes to infinity, beyond which the resource is inimitable. The right panel illustrates the
non-monotonic effect of $\alpha$. This result is at odds with the verbal literature in strategy which
closely links diminishing returns with time compression diseconomies and sustainability.

The ambiguous effect of diminishing returns on sustainability arises because there is not, in
fact, a clear link between the extent of diminishing returns and the extent of time compression
diseconomies. Time compression diseconomies are the extent to which costs fall with develop-
ment time, as given by $C'(T_F)$. As illustrated in the right panel of Figure 4.3, an increase in
$\alpha$ makes $C'(T_F)$ more negative for low values of $T_F$ and less negative for high values of $T_F$.\(^\text{11}\)

We argue that complexity is a more useful construct upon which to focus. As illustrated in
the left panel of Figure 4.3, increases in $K$ increase time compression diseconomies by making
$C'(T_F)$ everywhere more negative. This is what underlies the unambiguous effect of complexity
on sustainability. Moreover, operationalizing the extent of diminishing returns to effort might

\(^\text{11}\) For small $T_F$, the optimal effort is high and satisfies $z^*_T > 1$ so that the rate of progress $(z^*_T)^\alpha$ increases in $\alpha$. For high $T_F$, the optimal effort is low and satisfies $z^*_T < 1$ so that the rate of progress decreases in $\alpha$. 

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be much more difficult in empirical work than operationalizing the complexity of development projects. This is not to say that diminishing returns are unimportant. With constant returns ($\alpha = 1$), optimal resource development is instantaneous and the time dimension is lost from the analysis.

5. Implications for performance and development costs

For imitable resources, the follower’s optimal development time determines not only the sustainability of the leader’s competitive advantage but also measurable financial outcomes. Given the possibility to collect data on resource development budgets, we start by considering the implication of our model for the cost of resource development. One complication is whether to discount costs to the start of the project ($t = 0$) or to the end of the project ($t = T_F^*$). We consider both points of reference.

**Proposition 5.1.** Suppose the resource is imitable. (i) The present value at time $t = 0$ of the follower’s development costs, $C(T_F^*)$, are increasing in $\Delta_F$, decreasing in $r$, and non monotonic in $K$, $s$ and $\alpha$. (ii) The present value of development costs at time $t = T_F^*$, which are given by $C(T_F^*)e^{rT_F}$, is increasing in $\Delta_F$ and $K$, decreasing in $s$, independent of $r$ and non monotonic
An increase in the value of the resource to the follower, as given by $\Delta_F$, raises the optimal budget whether discounted to the start or the end of the project. The greater the value of the resource, the more the follower spends to compress the development time.

One might expect the optimal budget to increase with the complexity of the project net of spillovers, $(1 - s)K$, because harder problems require more effort to solve. This is what we find for the present value of costs at completion. However, the relationship can reverse for costs discounted to the start of the project. Complex problems take longer to solve. Because effort is optimally skewed towards the end of the project (Proposition 3.1), discounting can lower the present value at $t = 0$.

The effect of the cost of capital depends on the point of reference. When discounting back to the start of the project, an increase in the cost of capital lowers development costs. One might expect the reverse effect when discounting forward (i.e., compounding) to the end of the project. In fact, we find costs are independent of $r$ in this case. The impact of compounding is exactly offset by the fact that the firm responds to the increase in $r$ by taking longer to develop the resource (Proposition 4.2), which reduces costs. Now consider firm performance.

**Proposition 5.2.** Suppose that the resource is imitable. (i) The profits of the follower $\Pi_F(T_F^*)$ are increasing in $s$, $\pi_{cp}$ and $\pi_{cd}$ and decreasing in $K$ and $r$. (ii) The revenues of the leader $R_L(T_F^*)$ are increasing in $K$ and $\pi_{cd}$, decreasing in $s$, and non monotonic in $\pi_{cp}$.

The profits of the follower are falling in the complexity of developing the resource net of spillovers, $(1 - s)K$, and increasing in the follower’s profit flows, $\pi_{cp}$ and $\pi_{cd}$. In addition, profits are falling in the cost of capital since costs are incurred prior to revenues. The revenues of the leader are increasing in the sustainability of its competitive advantage. Hence, the complexity of resource development, which delays the follower, increases the leader’s revenues. Increases in the follower’s payoff when it has a competitive disadvantage $\pi_{cd}$ is good for the leader since it lowers the incentive of the follower to compress time. One implication is that it may not be in the interest of the leader to overly press its advantage (e.g., by entering segments that
are only marginally profitable to it but which are important to the follower). The effect of the competitive parity payoff $\pi_{cp}$ on the leader is ambiguous because on the one hand it increases the incentive of the follower to compress time and on the other hand it raises the leader’s payoff after imitation.

Thus far, we have sought to formalize the classic resource-based approach to sustainability where one firm has a valuable and rare resource that a competitor is seeking to imitate. One benefit of formalization is that it can facilitate extending the scope of the theory. To the extent that the base model is tractable, one can enrich the set of actions available to firms by adding prior stages to the model. We now turn to such extensions.

6. Licensing

Even when firms compete in output markets, they may want to cooperate in other realms such as resource development (Bradenburger and Nalebuff, 1996). One form of cooperation is the licensing and cross-licensing of patents, which is increasingly common (Shapiro, 2002).\(^\text{12}\) Another form of cooperation related to resource development is providing inputs to competitors. For example, Swatch, which owns many luxury watch brands, provides mechanical watch movement components to much of the Swiss luxury watch industry, although they have announced plans to discontinue this practice.\(^\text{13}\)

We extend our model to allow the leader to aid the follower’s resource development by licensing some of its knowledge about the resource development process. This raises the following questions. When is it possible for the leader and follower to reach a licensing agreement? How does this depend on whether or not resources are inimitable? What fraction of know-how should be licensed? We assume that full access to the leader’s knowledge reduces the complexity of the resource development project by a fraction $\bar{\ell} \in (0, 1)$. We allow for partial

\(^{12}\)High profile examples of cross-licensing agreements are those between Intel and AMD and between Sony and Samsung. These agreements can be asymmetric with the firm with the weaker patent portfolio making payments to the other firm. See “Accord Gives AMD MMX access” in *Electronic News* (1996) 42 (2099) p. 4 and “Patent Cross-Licensing Avoids Disputes” in *Electronic Component News* (2005) 49 (2) p. 62.

licensing, where the leader provides some $\ell \leq \bar{\ell}$ fraction of its knowledge. Licensing functions in an analogous way to spillovers in that complexity is reduced to $(1 - \ell)(1 - s)K$.\textsuperscript{14} The follower pays a fixed fee to the leader for the license. We assume a quadratic cost of progress in resource development ($\alpha = 1/2$).

We say that licensing at some level $\ell$ is feasible if there exist license fees that make both firms better off under licensing than without licensing. Feasibility requires that the gain to the follower from licensing (in terms of faster and cheaper resource development) is greater than the harm to the leader (in terms of a less sustainable competitive advantage). The condition for feasibility of licensing depends on whether or not the resource is imitable. We start with the case of inimitable resources.

**Proposition 6.1.** Suppose the leader’s resource is inimitable. (i) Licensing at some level $\ell$ is feasible if and only if

$$\frac{2\pi_{cp} - \pi_{cd} - \pi_{ca}}{\sqrt{\pi_{cp} - \pi_{cd}}} > (1 - \ell) r (1 - s) K$$

(LP1)

(ii) Inequality (L1) is easier to satisfy the greater is $\pi_{cp}$, $s$ and $\ell$ and the lower is $\pi_{ca}$, $\pi_{cd}$, $K$, and $r$. (iii) Necessary and sufficient conditions for licensing are $2\pi_{cp} - \pi_{cd} - \pi_{ca} > 0$ and $\ell$ sufficiently close to 1.

One can interpret condition (L1) as follows. The expression $2\pi_{cp} - \pi_{cd} - \pi_{ca} = (\pi_{cp} - \pi_{cd}) - (\pi_{ca} - \pi_{cp})$ is the effect of resource imitation on the combined revenue flows of the two firms. A necessary condition for feasibility when the resource is inimitable is that resource acquisition by the follower increases these revenue flows. If not, there is no scope to reach an agreement that makes both firms better off. Although necessary, an increase in combined revenue flows is not sufficient. The increase in combined revenues must be sufficiently great to offset the cost of resource development by the follower, which is not incurred without licensing. As a result, licensing depends on the complexity of the development process $((1 - \ell)(1 - s)K)$ and the cost of capital.

\textsuperscript{14} The assumption that $\bar{\ell} < 1$ assures that even with full licensing there is still some effort required for resource development. Even in an extreme case such as the follower buying equipment from the leader for an improved production process, there is still some effort required to install the equipment and train workers.
It is never feasible to license a small amount of knowledge about an inimitable resource. By definition, the cost of resource development without licensing exceeds the benefits to the follower. Consequently, a small amount of licensing, which only reduces development costs marginally, will not make both firms better off. Conversely, when the leader is licensing almost all of its knowledge (i.e., \( \ell \) close to 1), the cost of resource development is small and the feasibility of licensing depends only on whether combined revenues increase with imitation.

In summary, licensing for an inimitable resource is feasible when resource acquisition by the follower increases the combined revenue flows of the two firms and when the leader is licensing a sufficient amount of knowledge. Now consider resources which are imitated with or without licensing.

**Proposition 6.2.** Suppose the leader’s resource is imitable. (i) Licensing at a level \( \ell \) is feasible if and only if

\[
\frac{3\pi_{cp} - 2\pi_{cd} - \pi_{ca}}{\sqrt{\pi_{cp} - \pi_{cd}}} > (2 - \ell) r (1 - s) K 
\]  

(L2)

(ii) Inequality (L2) is easier to satisfy the greater is \( \pi_{cp} \), \( s \) and \( \ell \) and the lower is \( \pi_{ca} \), \( \pi_{cd} \), \( K \), and \( r \). (iii) In contrast to inimitable resources, licensing of imitable resources can occur even when \( 2\pi_{cp} - \pi_{cd} - \pi_{ca} < 0 \) and when \( \ell \) is arbitrarily close to 0.

We find that licensing is more likely to occur when the resource is imitable. Because the follower now develops the resource without licensing, the reduction in development costs that comes with licensing contributes to the benefits from licensing (in contrast to inimitable resources where the costs of resource development are deducted from the benefits). As a result, licensing can be feasible when resource imitation does not increase the combined revenue flow of the two firms and it may be desirable to license even a small amount of knowledge (i.e., \( \ell \) close to 0).

Despite the differences, comparative statics are the same across the two cases. Although one might expect that licensing would be easier to observe the more complex the resource, our theory predicts exactly the opposite. We find that licensing is more likely for less complex resource development processes with higher spillovers (i.e., lower \( (1 - s)K \)). The more costly it
is for a follower to imitate the more likely it is that the firm should keep its resource knowledge proprietary and exploit the sustainability of its competitive advantage.

So far we have considered the feasibility of licensing an arbitrary fraction $\ell$ of the leader’s knowledge. We now consider the optimal level of licensing when the leader can license any amount of knowledge up to $\bar{\ell}$. With efficient bargaining, firms should select the level of licensing that maximize their combined profitability (using the license fee to divide the gains).

**Proposition 6.3.** For both imitable and inimitable resources, the combined profits of the leader and follower are maximized either by licensing all of the leader’s knowledge ($\ell = \bar{\ell}$) or none of it ($\ell = 0$).

We find that licensing should be an all or nothing proposition. The more knowledge that is licensed, the more the follower is motivated to compress time because the benefits of imitation are closer at hand, which increases the returns to further licensing. Joint profits are then a convex function of the amount of knowledge licensed, which leads to a corner solution. Whether full licensing ($\ell = \bar{\ell}$) is preferred to no licensing ($\ell = 0$) is determined by substituting $\ell = \bar{\ell}$ into condition (L1) for inimitable resources or into condition (L2) for imitable resources.

7. Modeling the Creation of Resource Advantage

We now extend the model to encompass the initial creation of competitive advantage by the leader. We assume that the leader faces the same sort of resource development problem as the follower. We consider the following questions: Should the leader develop the resource? How long should it take? Does the leader’s competitive advantage translates into superior performance? How do the answers to these questions depend on resource imitability? Finally, what are the optimal levels of spillovers and causal ambiguity for the leader and the follower.

We add to the base model an initial stage where the leader develops the resource. We denote by $T_L > 0$ the time that the leader takes for resource development and continue to denote by $T_F$ the time spent on development by the follower. Because the follower starts its resource development after the leader’s development is complete, the follower acquires the
resource at time $t = T_L + T_F$. Prior to resource acquisition by the leader at time $t = T_L$ the two firms are identical and they both have revenue flows of $\pi_0 \geq 0$. We assume that the follower’s revenues decline when the leader acquires the resource and that giving both firms the resource increases their revenues: $\pi_{cd} \leq \pi_0 \leq \pi_{cp}$. The present value of the leader’s revenues are now

$$R_L(T_L, T_F) = \int_0^{T_L} \pi_0 e^{-rt} dt + \int_{T_F}^{T_L+T_F} \pi_{ca} e^{-rt} dt + \int_{T_L+T_F}^{\infty} \pi_{cp} e^{-rt} dt,$$

while those of the follower are

$$R_F(T_L, T_F) = \int_0^{T_L} \pi_0 e^{-rt} dt + \int_{T_L}^{T_L+T_F} \pi_{cd} e^{-rt} dt + \int_{T_L+T_F}^{\infty} \pi_{cp} e^{-rt} dt.$$

The leader faces the same resource development problem as the follower except that as the pioneer it does not benefit from spillovers. Thus, the leader faces the full level of complexity $K$. We assume that the cost of progress is quadratic ($\alpha = 1/2$). From Proposition 3.1, we have that the cost of resource development for the leader and follower are then

$$C_L(T) = \frac{rK^2}{e^{rT} - 1},$$

$$C_F(T) = \frac{r(1-s)^2K^2}{e^{rT} - 1}.$$

The profits of the two firms are then $\Pi_L(T_L) = R_L(T_L, T_F) - C_L(T_L)$ and $\Pi_F(T_L) = R_F(T_L, T_F) - C_F(T_F)e^{-rT_L}$.

### 7.1. The Development of Initable Resources

The development of an initable resource leads to a permanent increase in the leader’s revenue flows of $\Delta_L = \pi_{ca} - \pi_0$. The leader’s resource development problem in this case is then analogous to the resource development problem of the follower, only without spillovers. Substituting $\Delta_L$ for $\Delta_F$ and setting $s = 1$ in propositions 4.1 and 4.2 yields the following result.

**Proposition 7.1.** Suppose that the resource is initable. The leader can profitably develop
the resource if and only if $\sqrt{\Delta_L} > rK$, in which case its optimal development time is

$$T^*_L = -\frac{1}{r} \ln \left( 1 - \frac{rK}{\sqrt{\Delta_L}} \right).$$

(7.1)

The leader has higher profits than the follower.

The leader’s competitive advantage is unambiguously associated with superior performance. When the leader does not develop the resource, the two firms have the same profits. Relative to this benchmark, the follower must be worse off since it has a competitive disadvantage. Conversely, the leader must be better off because otherwise it would not choose to develop the resource. Thus, the leader has higher profits than the follower.

7.2. The Development of Imitable Resources

The development problem for imitable resources is complicated because the leader’s returns to resource development fall when the resource is imitated. Specifically, the initial benefit is $\pi_{ca} - \pi_0$ and this is reduced by $\pi_{ca} - \pi_{cp}$ with imitation. One can then define the quantity

$$\Delta^\text{im}_L = (\pi_{ca} - \pi_0) - (\pi_{ca} - \pi_{cp})(1 - \frac{r(1-s)K}{\sqrt{\Delta^\text{im}_F}}),$$

which gives the effective benefit of resource development in the case of imitable resources. Once this expression is defined, we show that the solution to the resource development problem has the familiar form.

**Proposition 7.2.** Suppose that the resource is imitable. The leader can profitably develop the resource iff $\sqrt{\Delta^\text{im}_L} > rK$, in which case its optimal development time is

$$T^*_L = -\frac{1}{r} \ln \left( 1 - \frac{rK}{\sqrt{\Delta^\text{im}_L}} \right).$$

(7.2)

The optimal development time of the follower is as before $T^*_F = -\frac{1}{r} \ln \left( 1 - \frac{rK}{\sqrt{\Delta^\text{im}_F}} \right)$.

We can now compare the development of inimitable and imitable resources.
Corollary 7.3. (i) The condition for profitable resource development is less restrictive and the development time is faster for inimitable resources than for imitable ones. (ii) For both types of resource, the development time of the leader $T_L^*$ is increasing in $K$, $r$ and $\pi_0$ and decreasing in $\pi_{ca}$. While the development time for inimitable resources is independent of $s$, $\pi_{cp}$ and $\pi_{cd}$, the development time of imitable resources is increasing in $s$, decreasing in $\pi_{cd}$ and non-monotonic in $\pi_{cp}$.

The result from part (i) follows immediately from the observation that the returns to resource development are greater when the resource is inimitable (i.e., $\Delta_L > \Delta_L^{im}$). In part (ii) we show that the comparative statics on the development time of the leader are the same for the two types of resources except for the parameters $s$, $\pi_{cd}$ and $\pi_{cp}$, which only effect the leader when the follower imitates. The non-monotonic effect of $\pi_{cp}$ arises because it both speeds imitation and lessens the impact on the leader.

7.3. Inter-Firm Comparisons and Optimal Spillovers

When both firms engage in resource development, there are several possible comparisons to consider. We impose the following restriction on the parameters

$$Kr < \min\{\Delta_L^{im}, \Delta_F\}, \quad (7.3)$$

which assures that both firms engage in resource development. We start with a comparison of their development times and development costs.

Proposition 7.4. Suppose that (7.3) holds and that the increase in revenues is greater for the first firm to develop the resource (i.e., $\pi_{ca} - \pi_0 > \pi_{cp} - \pi_{cd}$). (i) The leader spends more time on resource development than the follower unless all of the following hold: $s$ and $rK/\sqrt{\Delta_F}$ are both sufficiently small and $\pi_0 > \pi_{cd}$. (ii) The leader has a higher cost of resource development (discounted to the time of completion) than the follower unless both of the following hold: $s$ sufficiently small and $rK/\sqrt{\Delta_F}$ sufficiently close to 1.
The leader both spends more money on resource development and takes longer than the follower as long as there are sufficient spillovers. While an individual firm faces a tradeoff between speed and cost, sufficient spillovers allow the follower to outperform the leader on both dimensions. As spillovers become small, however, the firms increasingly face the same tradeoff between speed and cost. Then, whether the leader or the follower is faster and has higher costs depends on which firm has the greater incentive to compress time (i.e. whether $\Delta_F$ or $\Delta_L^{im}$ is larger). Interestingly, there is no clear ordering. Although we are assuming that the leader initially experiences a greater benefit from resource acquisition (i.e., $\pi_{ca} - \pi_0 > \pi_{cp} - \pi_{cd}$), the prospect of imitation means that its long-term benefit from resource acquisition is less than or equal to that of the follower (i.e., $\pi_{cp} - \pi_0 \leq \pi_{cp} - \pi_{cd}$). Which effect dominates depends on the sustainability of the leader’s advantage, which is what introduces the term $rK/\sqrt{\Sigma_F}$.

For inimitable resources, the leader’s competitive advantage gives it superior performance (Proposition 7.1). Interestingly, the link between competitive advantage and superior performance can break down when the resource is imitable because the costs associated with achieving the advantage may be large relative to the costs of imitation.

**Proposition 7.5.** Suppose that (7.3) holds. There exists an $\bar{s} \in (0, 1)$ which is increasing in $K$ such that the leader has higher profits than the follower if and only if $s < \bar{s}$.

The association between resource asymmetry and superior performance need not be tautological – a central concern of Priem and Butler (2001) – once one accounts for the cost of resource development. Figure 7.1 illustrates how firm profits depends on the level of spillovers. Without spillovers ($s = 0$), the follower faces the same cost function as the the leader, but it has a period of competitive disadvantage. Hence, the leader must have superior performance. As spillovers approach the upper limit of 1, the follower’s cost of resource development goes to zero. In addition, the time required for imitation goes to zero, which eliminates the period of competitive advantage for the leader and gives the firms the same return to resource development. With the same returns and lower costs, it is now the follower that has supe-

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15The condition $\pi_{ca} - \pi_0 > \pi_{cp} - \pi_{cd}$ is a common feature of standard IO models of competition. For example, it holds in a Cournot model with linear demand where the resource reduces marginal costs.
prior performance. The more complex resource development, the more important are the cost savings from spillovers and the more likely it is that the follower has higher profits.

Firms can take a variety of steps to affect the level of spillovers. Leaders can reduce spillovers and increase causal ambiguity by adopting HR policies that reduce the turnover of key employees (Cappelli, 1999), through the geographic dispersion of development activities (Zhao, forthcoming) and by patenting (Mansfield, 1985). Followers can increase spillovers by investing in R&D activities that increase their absorptive capacity (Cohen and Levinthal, 1990), by more closely aligning their strategy and organization with that of the leader so as to facilitate interorganizational learning (Hannan and Freeman, 1989) and by locating facilities near to the leader’s facilities (Fujita et al., 2000). As illustrated in Figure 7.1, the relationship between spillovers and profits need not be monotonic. We now consider the extent of such non-monotonicities by looking at whether or not firms maximize their profits at extreme levels of spillovers.

**Proposition 7.6.** Suppose that (7.3) holds. (i) The optimal level of spillovers for the Leader
is \( s = 0 \). (ii) The optimal level of spillovers for the follower is less than \( s = 1 \) if

\[
Kr > \frac{\sqrt{\Delta F} \cdot 4}{3 + \frac{\pi_{ca} - \pi_{cd}}{\pi_{cp} - \pi_{cd}}}.
\] (7.4)

The leader always benefits from decreasing spillovers, which are unambiguously harmful in our model because they speed imitation. Spillovers benefit the follower through both faster and cheaper resource development. Despite these effects, we show that too high a level of spillovers can be harmful to the follower. The reason is the impact on the leader’s speed of resource development. The faster the leader anticipates being imitated, the less incentive is has to compress time. Because this delays the follower’s resource acquisition, slower development by the leader reduces the present value of the follower’s profits. When inequality (7.4) holds, the net effect of increased spillovers is negative for sufficiently high \( s \). Since (7.3) implies that

\( Kr < \sqrt{\Delta F} \),

condition (7.4) only holds if \( \pi_{ca} \) is large relative to \( \pi_{cp} \): the greater the gap between \( \pi_{ca} \) and \( \pi_{cp} \), the greater the demotivation of the leader from speedy imitation by the follower.

Spillovers are inversely related to the degree of causal ambiguity. While Proposition 7.6 confirms the positive association between causal ambiguity and the performance of leaders, we show that followers as well may benefit from an increase in causal ambiguity. This result, which is contrary to the received wisdom in strategy, arises because higher causal ambiguity assures that the leader has sufficient payoff from resource development to advance quickly.

8. Conclusion

We have sought to develop a richer and more dynamic resource-based theory of sustainable competitive advantage. Our theory, with its focus on resources developed in projects with identifiable stopping times, is somewhat more specialized than the received verbal theories of the RBV. To a large extent, however, the strategy of modern corporations can be seen as a series of discrete resource development projects: IT implementation projects for CRM and ERP systems, new product development projects, the construction of new production facilities
and the re-engineering or offshoring of particular business processes. Given their ubiquity, we believe that focusing on discrete projects is a promising avenue for both empirical research and for the development of theory that is relevant to strategy practice.

There are many, many possible directions to further develop a strategic theory of resource development. In this paper, we consider sequential development projects by a leader and a follower. It would be interesting to study parallel resource development. In this paper, we consider firms that are homogeneous but for the possession of the focal resource. There are a variety of ways that one could introduce firm asymmetries. Firms could vary in the possession of complementary resources that affect the returns to developing resources or they could vary in the time-cost tradeoffs they face due to different development capabilities or they could vary in their cost of capital. Another possibility for theory development it to introduce uncertainty, either in the returns to having a resource or in the resource development process itself.

References


Appendix

Proof of Proposition 3.1 The proof is an application of the analysis in Section 2 of Lucas (1971). Let $k_t = (z_t)^\alpha$ be the rate of progress towards the completion of the project. Denote the total progress up to time $T$ by $K(T) = \int_0^T k_t dt$. The firm’s cost minimization problem is

$$C(T_F) = \min_{z_t \geq 0} \int_0^{T_F} z_t e^{-rt} dt$$

s.t. $K(0) = 0$, $K(T_F) = (1-s)K$. 

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The Hamiltonian for this problem is \( H(z_t) = -z_t e^{-rt} + \lambda_t(z_t)^\alpha \) and the necessary and sufficient conditions for an optimum are that the following holds:

\[
\alpha \lambda_t(z_t)^{(1-\alpha)} = e^{-rt} \quad (9.1)
\]
\[
k_t = (z_t)^\alpha \quad (9.2)
\]
\[
\frac{d\lambda_t}{dt} = 0 \quad (9.3)
\]
\[
K(0) = 0, \; K(T_F) = (1-s)K \quad (9.4)
\]

Using (9.3), we have that \( \lambda_t = \lambda \) and \( z_t^* = \left( \alpha \lambda e^{rt} \right)^{1/(1-\alpha)} \) by (9.1). This, together with (9.2), implies that \( K(T_F) - K(0) = \int_0^{T_F} \left( \alpha \lambda e^{rt} \right)^{\alpha/(1-\alpha)} dt = \frac{1-\alpha}{\alpha r} \left( \alpha \lambda \right)^{\alpha/(1-\alpha)} \left( e^{rT_F \alpha/(1-\alpha)} - 1 \right) \).

(9.4) then implies that \( (\alpha \lambda)^{1/(1-\alpha)} = \left( \frac{\alpha}{1-\alpha} r(1-s)K \right) / \left( e^{rT_F \alpha/(1-\alpha)} - 1 \right) \right)^{1/\alpha} \) and 

\[
z_t^*(T_F) = e^{rt/(1-\alpha)} \left( \frac{\alpha}{1-\alpha} \right) e^{rT_F \alpha/(1-\alpha)} \left( e^{rT_F \alpha/(1-\alpha)} - 1 \right)^{1/\alpha}. \]

The expression for \( C(T_F) \) then follows from the definition \( C(T_F) = \int_0^{T_F} z_t^*(T_F)e^{-rt}dt. \)

**Proof of Proposition 4.1** The first order condition \( R'_F(T_F) - C'(T_F) = 0 \) for the follower’s optimization problem yields

\[
-D_F e^{-rT_F} + \left( \frac{(1-s)Kr}{e^{T_F \alpha/(1-\alpha)} - 1} \right)^{1/\alpha} \left( \frac{\alpha}{1-\alpha} \right) e^{rT_F \alpha/(1-\alpha)} = 0, \quad (9.5)
\]

which we can rewrite as

\[
\frac{1}{1 - e^{-rT_F \alpha/(1-\alpha)}} = \frac{\Delta_F^\alpha}{(1-s)Kr} \left( \frac{1-\alpha}{\alpha} \right)^{1-\alpha}. \quad (9.6)
\]

Note the LHS of (9.6) is everywhere decreasing in \( T_F \) while the RHS is a constant. Hence, there is at most one value of \( T_F \) at which (9.6) is satisfied. Moreover, the lower bound on the LHS is 1 and hence a unique solution with \( T_F < \infty \) exists if and only if (IN) holds. This solution must yield a positive payoff and must be a global maximum since \( \lim_{T_F \to 0} \Pi_F(T_F) = -\infty \) and \( \lim_{T_F \to \infty} \Pi_F(T_F) = 0. \)

The comparative statics on (IN) with respect to \( \Delta_F, \; K \) and \( s \) hold by inspection. The effect of \( \alpha \) is given by

\[
\frac{\partial}{\partial \alpha} \left( \frac{(r(1-s)K)^{1/\alpha}}{(1-\alpha)/(1-\alpha)^{1/\alpha}} \right) = \frac{(r(1-s)K)^{1/\alpha}}{\alpha^2((1-\alpha)/(1-\alpha)^{1/\alpha})} \left( \ln \left( \frac{1-\alpha}{\alpha} \right) - \ln(r(1-s)K) + 1 \right),
\]

whose sign is determined by \( \left( \ln \left( \frac{1-\alpha}{\alpha} \right) - \ln(r(1-s)K) + 1 \right), \) which is increasing in \( \alpha \). For \( \alpha \) sufficiently close to 0 the derivative is positive while for \( \alpha \) sufficiently close to 1 the derivative is negative.

**Proof of Proposition 4.2** Solving the first order condition (9.6) for \( T_F \) yields (4.1).
show that $T_F^*$ is increasing in $r$ it is sufficient to show that $g(r) = \frac{1}{r} \ln \frac{1}{1-rz}$ is increasing in $r$ for $rz < 1$. We have that $g'(r)$ has the same sign as $rz -(1-rz) \ln \left( \frac{1}{1-rz} \right)$ and that this is increasing in $r$ and equal to 0 for $r = 0$. Hence, $g'(r) > 0$. The other comparative statics results are straightforward. ■

Proof of Proposition 5.1 (i) We have the present value of costs at $t = 0$ are $C(T_F^*) = (1-s)K \left( (\Delta_F^+(1-\alpha)/\alpha)^{-(1-\alpha)} - r(1-s)K /\left((1-\alpha)/\alpha\right)^{(1-\alpha)/\alpha} \right)$. By inspection, this is increasing in $\Delta_F$ and decreasing in $r$. For $(1-s)K$ sufficiently close to zero, costs are increasing in $(1-s)K$, while for $(1-s)K$ sufficiently close to $\Delta_F^+(1-\alpha)/\alpha^{-(1-\alpha)/r}$ costs are decreasing in $(1-s)K$. For $\Delta_F = 2$ and $r(1-s)K = 1/2$, we have that costs are decreasing in $\alpha$ up to about 0.704 and increasing thereafter, which establishes that the effect of $\alpha$ can be non-monotonic.

(iii) We have the present value of costs at $t = T_F^*$ are

$$C(T_F^*)e^{rT_F^*} = (1-s)K \Delta_F^{1-\alpha} / ((1-\alpha)/\alpha)^{2-\alpha(1-\alpha)}.$$ 

By inspection, this is increasing in $\Delta_F$ and $(1-s)K$ and independent of $r$. As $(1-\alpha)/\alpha)^{2-\alpha(1-\alpha)}$ is non-monotonic in $\alpha$, we have that costs are non-monotonic for $\Delta_F$ sufficiently close to 1. ■

Proof of Proposition 5.2 (i) Suppose that an effort profile $z_t$ is optimal for some value of $\pi_{cd}$. Increasing $\pi_{cd}$ while holding fixed the effort profile increases profits due to increased revenues at the same costs and hence profits also increase for the effort profile that is optimal for the increased value of $\pi_{cd}$. The same argument establishes that profits are increasing in $\pi_{cp}$.

Suppose an effort profile $z_t$ is optimal for some value of $(1-s)K$. Decreasing $(1-s)K$ while holding fixed the effort profile results in earlier completion for the same cost and hence higher profits and hence profits will also be higher for the optimal effort profile for the lower value of $(1-s)K$. Hence, profits are falling in $(1-s)K$.

Finally, suppose an effort profile is optimal for some value of $r$. Decreasing $r$ while holding fixed the effort profile results in an increase in profits since the earlier occurring costs are inflated less than revenues and hence profits will also be higher for the reoptimized effort. Hence, profits are falling in $r$.

(ii) We have that

$$R_L(T_F^*) = \frac{\pi_{ca}}{r} - \frac{\pi_{ca} - \pi_{cp}}{r} e^{-rT_F^*}$$

$$= \frac{\pi_{ca}}{r} - \left( \frac{\pi_{ca} - \pi_{cp}}{r} \right) \left( 1 - \frac{r(1-s)K}{(\pi_{cp} - \pi_{cd})(1-\alpha)/\alpha} \right)^{(1-\alpha)/\alpha}$$

By inspection, this is increasing in $\pi_{cd}$, $\pi_{ca}$ and $(1-s)K$. For $\alpha = 1/2$ we have

$$\frac{\partial R_L(T_F^*)}{\partial \pi_{cp}} = \left( \frac{r(1-s)K}{2} \right) \left( \frac{\pi_{ca} + \pi_{cp} - 2\pi_{cd}}{(\pi_{cp} - \pi_{cd})^{3/2}} \right) - 1,$$

which is negative for $r(1-s)K$ sufficiently small and positive for $r(1-s)K$ sufficiently close to its upper bound $\sqrt{\pi_{cp} - \pi_{cd}}$. Hence, the effect of $\pi_{cp}$ is non-monotonic. ■
Proof of Proposition 6.1 Suppose that $\alpha = 1/2$ and that the resource is inimitable so that $\sqrt{\Delta F} \leq r(1-s)K$. (i) Consider some level of licensing $\ell \in (0,1)$. Suppose with licensing it is now optimal for the follower to develop the resource. (Otherwise licensing is not desirable since the total profits of the two firms are unchanged and it is impossible to make them strictly better off.) With licensing at the level $\ell$, the combined profits of the leader and follower can be written as

$$\Pi_T(\ell) = \left(\frac{\pi_{cd}}{r} + \frac{\pi_{ca}}{r}\right)(1 - e^{-T_F(\ell)r}) + 2\frac{\pi_{cp}}{r} e^{-T_F(\ell)r} - (1 - l)^2 C(T_F^*(\ell)).$$

(9.7)

Since licensing has the same effect on the followers optimal development time as spillovers, we have that

$$T_F^*(\ell) = -\frac{1}{r} \ln(1 - \frac{r'(1-\ell)(1-s)K}{\sqrt{\Delta F}}).$$

(9.8)

The present value of industry profits is then

$$\Pi_T(\ell) = \left(\frac{\pi_{cd}}{r} + \frac{\pi_{ca}}{r}\right) \left(\frac{r'(1-\ell)(1-s)K}{\sqrt{\Delta F}}\right) + 2\frac{\pi_{cp}}{r} \left(1 - \frac{r'(1-\ell)(1-s)K}{\sqrt{\Delta F}}\right) - (1-\ell)(1-s)K \left(\Delta_F^{1/2} - r'(1-\ell)(1-s)K\right).$$

Without licensing ($\ell = 0$) we have that the present value of industry profits with an inimitable resource is

$$\Pi_I = \frac{\pi_{cd}}{r} + \frac{\pi_{ca}}{r}.$$

Assuming that the follower wants to develop the resource, licensing at a level $\ell$ is desirable iff $\Pi_T(\ell) > \Pi_I$, which is equivalent to (L1). Because $\Pi_T(\ell) > \Pi_I$ assures that resource development increases industry profits, this condition also assures that it increases the profits of the follower.

(ii) The comparative statics on (L1) for $\ell$, $s$, $K$, $r$, and $\pi_{ca}$ follow by inspection. The derivative of the LHS of (L1) w.r.t $\pi_{cp}$ is $(2\pi_{cp} + \pi_{ca} - 3\pi_{cd})/(2(\pi_{cp} - \pi_{cd})^{3/2}) > 0$ and w.r.t. $\pi_{cd}$ is $-(\pi_{ca} - \pi_{cd})/(2(\pi_{cp} - \pi_{cd})^{3/2}) < 0$.

(iii) Since the RHS of (L1) is positive, a necessary condition for (L1) to hold is that $2\pi_{cp} - \pi_{cd} - \pi_{ca} > 0$. This is not sufficient since we can rewrite the LHS as $\sqrt{\Delta F} - (\pi_{ca} - \pi_{cp})/\sqrt{\Delta F}$ and this is less than $\sqrt{\Delta F}$ and we know that $\sqrt{\Delta F} \leq r(1-s)K$ for inimitable resources. Hence, (L1) is satisfied if and only if $2\pi_{cp} - \pi_{cd} - \pi_{ca} > 0$ and $\ell$ is sufficiently large. ■

Proof of Proposition 6.2 Suppose that $\alpha = 1/2$ and that $\sqrt{\Delta F} > r(1-s)K$ so that the resource is imitable. (i) Total industry profits are given by $\Pi_T(\ell)$, as defined in Proposition 6.1. Moreover, since the follower develops the resource even without licensing, profits without licensing are now given by $\Pi_T(0)$. Licensing at a level $\ell \in (0,1)$ increases the total profits of the leader and follower iff $\Pi_T(\ell) > \Pi_T(0)$, which with some algebra is equivalent to (L2). (ii) The comparative statics on (L2) for $\ell$, $s$, $K$, $r$, and $\pi_{ca}$ follow by inspection. The derivative of the LHS of (L2) w.r.t $\pi_{cp}$ is $(3\pi_{cp} + \pi_{ca} - 4\pi_{cd})/(2(\pi_{cp} - \pi_{cd})^{3/2}) > 0$ and w.r.t. $\pi_{cd}$ is $-(\pi_{ca} + \pi_{cp} - 2\pi_{cd})/(2(\pi_{cp} - \pi_{cd})^{3/2}) < 0$. (iii) Suppose that $2\pi_{cp} - \pi_{cd} - \pi_{ca} = 0$. In the limit

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as $\ell \to 0$, we have that inequality (L2) becomes $\sqrt{\Delta_F} > r(1 - s)K$, which is satisfied as this is the condition that the resource is imitable.

**Proof of Proposition 6.3** We have that $\partial^2 \Pi_T / \partial \ell^2 = 2r(1 - s)^2K^2 > 0$ and total industry profits are a convex function of the amount of knowledge licensed. Hence, if industry profits are increased by licensing an amount $\ell < \bar{\ell}$, they are increased more by licensing $\bar{\ell}$. Note that this does not rule out $\ell = 0$ being optimal.

**Proof of Proposition 7.2 and Corollary 7.3** The problem of the follower is unchanged from that in the proof of proposition 4.2. The leader maximizes

$$
\Pi_L (T_L) = \frac{\pi_o}{r}(1 - e^{-rT_L}) + \frac{\pi_{ca}}{r}(e^{-rT_L} - e^{-r(T_L + T_F^*)}) + \frac{\pi_{cp}}{r}(e^{-r(T_L + T_F^*)}) - C_L (T_L).
$$

For $rK < \sqrt{\Delta_{L}^{im}}$, one can solve this equation for an interior $T_L$ yields, which is given by (7.2). This establishes Proposition 7.2. Part (i) of Corollary 7.3 follows from $\Delta_{L}^{im} < \Delta_{L}$. The comparative statics when $T_L^*$ is given by (7.1) hold by inspection. Suppose the resource is inimitable and $T_L^*$ is given by (7.2). To establish that $T_L^*$ is increasing in $K$, note that (7.2) can be rewritten as $T_L^* = -\frac{1}{r} \ln \left(1 - \frac{r}{\sqrt{\Delta_{L}^{im} / K^2}} \right)$ and $\partial (\Delta_{L}^{im} / K^2) / \partial K = -\frac{1}{K^2} (\Delta_{L}^{im} + \pi_{cp} - \pi_0) < 0$. To establish that $T_L^*$ is increasing in $r$, it is sufficient to show that (7.2) can be rewritten as $T_L^* = -\frac{1}{r} \ln \left(1 - \frac{K}{\Delta_{L}^{im}} \right)$ and $\partial (\Delta_{L} / r^2) / \partial r = -\frac{1}{r^2} (\Delta_{L}^{im} + \pi_{cp} - \pi_0) < 0$. As for the comparative statics w.r.t. $\pi_{cp}$, note first that

$$
\partial \Delta_{L}^{im} / \partial \pi_{cp} = \frac{1}{2\Delta_F \sqrt{\Delta_F}} (2\Delta_F (\Delta_{F} - rK (1 - s)) - rK (1 - s)(\pi_{ca} - \pi_{cp})).
$$

Because (IN) is not satisfied, $\Delta_{F} - rK (1 - s) > 0$ and the sign of $\partial \Delta_{L}^{im} / \partial \pi_{cp}$ depends on the size of $(\pi_{ca} - \pi_{cp})$. The comparative statics w.r.t. $\pi_{ca}$, $\pi_{cd}$, $\pi_0$, and $s$ follow by inspection.

**Proof of Proposition 7.4** Suppose that $K^* < \min\{\Delta_{L}^{im}, \Delta_{F}\}$. Then the resource is imitable and the leader develops it. Suppose that $\pi_{ca} - \pi_0 > \pi_{cp} - \pi_{cd}$. (i) We have that $T_L^* > T_F^*$ is equivalent to $\Delta_{F} > (1 - s)^2\Delta_{L}^{im}$. The expression $(1 - s)^2\Delta_{L}^{im}$ is monotonically decreasing in $s$. If $\Delta_{F} > \Delta_{L}^{im}$ then $T_L^* > T_F^*$ for all $s \in [0, 1]$ while if $\Delta_{F} \leq \Delta_{L}^{im}$ then $T_L^* > T_F^*$ only holds for $s$ sufficiently close to 1. We have that $\Delta_{F} > \Delta_{L}^{im}$ is equivalent to

$$
\pi_{cp} - \pi_{cd} > (\pi_{ca} - \pi_0)w + (\pi_{cp} - \pi_0)(1 - w)
$$

for $w = r(1 - s)K / \sqrt{\Delta_F} \in (0, 1)$. Recall that $\pi_{ca} - \pi_0 > \pi_{cp} - \pi_{cd}$. If $\pi_{cd} = \pi_0$ then inequality (9.9) never holds while for $\pi_0 > \pi_{cd}$ it only holds for $w$ sufficiently small.

(ii) We have $e^{rT_{L}}C(T_L^*) > e^{rT_{F}}C(T_F^*)$ is equivalent to $\Delta_{L}^{im} > (1 - s)^2\Delta_{F}$. The expression $(1 - s)^2\Delta_{L}^{im}$ is a decreasing, convex function of $s$ which is equal to zero for $s = 1$. The expression $\Delta_{L}^{im}$ is a linear decreasing function of $s$ which is positive for $s = 1$. If $\Delta_{L}^{im} > \Delta_{F}$ then $e^{rT_{L}}C(T_L^*) > e^{rT_{F}}C(T_F^*)$ for all $s \in [0, 1]$ while if $\Delta_{L}^{im} \leq \Delta_{F}$ then the leader’s costs are only higher if $s$ is sufficiently high. Following the analysis in part (i), we have that $\Delta_{L}^{im} > \Delta_{F}$ as long as $rK / \sqrt{\Delta_F}$ is sufficiently large.
Proof of Proposition 7.5 Note that \(1 - e^{-rT_F^*} = \frac{r(1-s)K}{\sqrt{\Delta_F}}\). The difference in revenues is

\[
R_L^* - R_F^* = \int_{T_L^*}^{T_F^*+T_L^*} (\pi_{ca} - \pi_{cd}) e^{-rt} dt = \frac{1}{r}(\pi_{ca} - \pi_{cd}) e^{-rT_L^*}(1 - e^{-rT_F^*})
\]

\[
= e^{-rT_L^*}(\pi_{ca} - \pi_{cd})(1 - s)K \sqrt{\Delta_F}
\]

Since \(C_L(T_L^*) = K \left(\sqrt{\Delta_L^{in}} - rK\right)\) and \(e^{rT_L^*} = \sqrt{\Delta_L^{im}/(\sqrt{\Delta_L^{in}} - rK)}\), we have that \(C_L(T_L^*)e^{rT_L^*} = K\sqrt{\Delta_L^{in}}\). In addition, \(C_F(T_F^*) = (1-s)K(\sqrt{\Delta_F} - r(1-s)K)\). The difference in costs (discounted to \(t = 0\)) is then

\[
C_L(T_L^*) - C_F(T_F^*)e^{-rT_L^*} = e^{-rT_L^*} \left(C_L(T_L^*)e^{rT_L^*} - C_F(T_F^*)\right)
\]

\[
e^{-rT_L^*}K \left(\sqrt{\Delta_L^{im}} - (1-s)\sqrt{\Delta_F} + r(1-s)^2K\right)
\]

The difference in profits is then \(\Pi_L^* - \Pi_F^* = R_L^* - R_F^* - C_L(T_L^*) - C_F(T_F^*)e^{-rT_L^*} = e^{-rT_L^*}K(1-s)W\) where

\[
W = \left(\pi_{ca} - \pi_{cd} + \sqrt{\Delta_F} - \frac{\sqrt{\Delta_L^{im}}}{1-s} - r(1-s)K\right). \text{ Then } \Pi_L^* > \Pi_F^* \text{ iff } W > 0.
\]

To establish the existence of an \(\bar{s}\) such that \(\Pi_L^* > \Pi_F^* \text{ iff } s < \bar{s}\), we show that \(W > 0\) for \(s = 0\), \(\lim_{s \to 1} W < 0\), and that \(\partial W/\partial s < 0\). By inspection \(\lim_{s \to 1} W < 0\). Conversely, for \(s = 0\) we have

\[
\lim_{s \to 0} W = \frac{1}{\sqrt{\Delta_F}} \left(\pi_{ca} - \pi_{cd} + \sqrt{\Delta_F} - \sqrt{\Delta_L^{im}}\sqrt{\Delta_F}\right) > 0
\]

where the inequality follows from \(\pi_{ca} - \pi_{cd} > \max\{\Delta_L^{in}, \Delta_F\}\). Finally, we have

\[
\frac{\partial W}{\partial s} = rK - \frac{rK}{(1-s)^2} - \frac{\pi_{ca} - \pi_{cd}}{(1-s)\sqrt{\Delta_L^{im}\Delta_F}} < 0
\]

since \(\sqrt{\Delta_L^{im}} > rK\). Hence there exists a unique \(\bar{s}\) such that the profits of the leader are higher \(\text{iff } s < \bar{s}\). We have that

\[
\frac{\partial W}{\partial K} = -r(1-s) - \frac{\pi_{ca} - \pi_{cd}}{2\sqrt{\Delta_L^{im}\sqrt{\Delta_F}}} < 0.
\]

Using the implicit function theorem, we have that \(\partial s/\partial K = -\partial W/\partial K / \partial W/\partial s < 0\).

Proof of Proposition 7.6 To establish that the optimal \(s\) for the follower is less than 1, it is sufficient to show that \(\partial \Pi_F^*/\partial s < 0\) at \(s = 1\). The follower’s profits are
\[ \Pi_F^* = \frac{e^{-rT_F^*}}{r} \left( \pi_0 e^{rT_F^*} - 1 \right) + \left( \pi_{cd}(1 - e^{-rT_F^*}) + \pi_{cp} e^{-rT_F^*} - rC_F(T_F^*) \right) \]
\[ = \left( \frac{1}{r} - \frac{K}{\sqrt{\Delta^i_L}} \right) \left( \pi_{cp} - 2\sqrt{\Delta_F^i r(1 - s)K + r^2(1 - s)^2K^2} \right) + \pi_0 \frac{K}{\sqrt{\Delta^i_L}} \]

We then have that
\[ \frac{\partial \Pi_F^*}{\partial s} \bigg|_{s=1} = -\left( Kr(3\pi_{cp} - 4\pi_{cd} + \pi_{ca}) - 4(\pi_{cp} - \pi_{cd})\sqrt{\pi_{cp} - \pi_0} \right) \frac{K}{2\sqrt{\pi_{cp} - \pi_0}\sqrt{\pi_{cp} - \pi_{cd}}} \]
so that \( \partial \Pi_F^*/\partial s < 0 \) at \( s = 1 \) iff condition (7.4) holds.