THE ROLE OF COMPETITIVE AMPLIFICATION IN EXPLAINING SUSTAINED PERFORMANCE HETEROGENEITY

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Abstract

This paper introduces a formal model that highlights the importance of competitive amplification in creating sustained performance heterogeneity. The model predicts that amplification and the resulting heterogeneity are largest in markets with resources that are scale-free, carry high sunk cost, depreciate rapidly, and/or exhibit strong time-compression diseconomies. In markets with resources that have such amplifying characteristics, an advantaged firm has a stronger incentive to invest than a follower, leading to the emergence of high heterogeneity and potentially even a monopoly. In the absence of amplifying resource characteristics, performance differences are attenuated, leading to relatively low heterogeneity. The Markov perfect equilibrium (MPE) model in this paper can be extended for further research on resource evolution under uncertainty.

1 Introduction

Resource accumulation provides an important explanation for the emergence of sustained performance differences across firms (Dierickx and Cool 1989, Maritan and Peteraf 2011). Small, idiosyncratic differences are the seeds of a process that can set firms on different paths of resource evolution (Ahuja and Katila 2004). Limits to imitation (and substitution), for instance due to time-compression diseconomies or causal ambiguity, act as isolating mechanisms ensuring that any resource and performance differences are not rapidly competed away (Rumelt 1984, Dierickx and Cool 1989, Barney 1991).

Ultimately, firms' investment decisions form the basis of changes in resource positions and thus of accumulation patterns. However, we know little about how between-firm differences in investment incentives shape resource accumulation paths and the resulting evolution of performance differences. For instance, in some markets an advantaged firm might have a larger incentive to extend its lead than a disadvantaged firm's incentive to catch up, thus amplifying any performance differences over time. In other markets a disadvantaged firm might have the larger investment incentive, thus attenuating performance differences over time, even in the absence of imitation and substitution. Thus, amplification (or attenuation) due to differential investment incentives provides a potentially important mechanism for the emergence of performance differences distinct from diverging accumulation paths due to imitation and substitution barriers. Competitive amplification could explain why performance heterogeneity in some industries is much higher than in others (McGahan and Porter 1997, Vanneste 2017), and it can inform managers about in which situations small advantages have a high chance to translate over time into large competitive differences.

To investigate the role of amplification in the emergence of performance heterogeneity, in this paper I introduce a formal model of competitive dynamics with endogenous resource investment under uncertainty. The model is based on Markov perfect equilibrium (MPE) industry dynamics (Ericson and Pakes 1995), a workhorse model in present-day industrial organization (IO) economics. A key assumption in this model is that a firm chooses its level of resource investment to optimize the expected value of future cash flows. The MPE modeling framework is well-suited to study the relationships between competition, resource accumulation dynamics, and sustained performance heterogeneity, but so far has garnered little attention in strategy research.

A key resource characteristic in the model that has been largely absent from prior literature on accumulation is scalability. A resource is highly scalable (or scale-free) if it is not capacity-constrained and thus carries little opportunity cost when used (Levinthal and Wu 2010). For instance, brands, technologies, and patents are highly scalable, while plants and personnel are capacity-constrained ("non-scale-free"). We know that resource scalability is a salient characteristic in strategic decisions such as diversification. However, Dierickx and Cool (1989) do not explicitly distinguish on this characteristic, for instance combining resources at both ends of the spectrum in their statement that "capacity and brand loyalty are [credible vehicles for entry deterrence]" (p. 1508). Also later accumulation literature includes both resource types. For example, some empirical papers study scale-free resources such as technological assets and capabilities (Thomke and Kuemmerle 2002, Knott, Bryce, and Posen 2003), while others study capacity-constrained ones such as production facilities (Pacheco-de Almeida, Henderson, and Cool 2008).

Note that scalability is distinct from the concept of asset mass efficiencies. The latter refers to "the extent that adding increments to an existing asset stock is facilitated by possessing high levels of that stock" (Dierickx and Cool 1989, p. 1507). By contrast, scalability is the extent to which resources are capacity constrained. To ensure this distinction in the model, I assume that scalability is independent from the ease to acquire resources and the potential benefits deriving from them: each unit of resources—scalable or not—can reduce a firm's cost base by the same amount.

The model in this paper predicts that scalability has a strong effect on amplification and the resulting performance differences. In markets where firms compete for capacity-constrained resources (i.e., with low scalability), the disadvantaged firm tends to have an incentive to catch up, leading to attenuation of performance differences and lower heterogeneity. In markets where firms compete for highly scalable resources, the advantaged firm often has an incentive to extend its lead. Whether performance differences are amplified in markets with highly scalable resources also depends on other resource characteristics, such as sunk cost, depreciation, and the level of time-compression diseconomies. Markets with resource characteristics that exhibit strong amplification tend to result in competitive outcomes with strong performance heterogeneity. Competitive amplification can even lead to the emergence of a monopoly, because investment incentives can become so asymmetric that the best strategy of a disadvantaged firm is to stop investing in its resource base.

Perhaps the most unexpected insight from the model is that higher depreciation can lead to more performance differences. Based on the arguments in Dierickx and Cool (1989), higher depreciation ("asset erosion") makes it harder to defend any resource advantages and thus should lead to less performance heterogeneity. However, rapidly depreciating resources also require higher investments to maintain, making them more expensive. The model in this paper indicates that more expensive resources tend to tilt the investment incentives in favor of the advantaged firm, leading to higher amplification. In the situations studied here, the amplification effect turns out to be stronger than the asset erosion effect from simple accumulation, leading to more performance heterogeneity in markets with high resource depreciation.

Finally, the results of this paper hold a word of caution for firms with strong competitive advantages. They need to stay particularly vigilant about not being displaced from their seemingly comfortable competitive positions. The reason is that such dominant positions tend to arise in markets with strong competitive amplification. If the incumbent firm is too lax, the amplification dynamics that had propelled it into its dominant position can boomerang on itself and similarly propel a competitor to displace the incumbent.

2 Prior RBV models

The resource-based view (RBV) is a central theory in the strategy literature, explaining why performance differences can persist even among firms competing in the same market (Wernerfelt 1984, Barney 1991, Peteraf 1993). From the outset, formal and simulation models have played an important role in For instance, Lippman and Rumelt (1982) add uncertainty in production costs to the neo-classical entry model, showing that such causal ambiguity can lead to industries with significant performance differences among competitors. Makadok and Barney (2001) use a two-stage game theoretic model to study strategic factor market intelligence, another potential source of firm-specific heterogeneity. Similarly, other models have investigated the role of complementarity (Adegbesan 2009), scale-free resources (Levinthal and Wu 2010, Asmussen 2015), asymmetries due to extant resource stocks (Wernerfelt 2011), customization of generic resources (Jacobides, Winter, and Kassberger 2012), strategic factor markets (Chatain 2014), and higher-order resources (Wibbens 2019).

Since the RBV is a theory of firms competing for scarce resources, it is unsurprising that the above models use competitive settings, such as atomistic price taking (Lippman and Rumelt 1982), oligopolistic competition (Levinthal and Wu 2010), and non-coalitional game theory (Adegbesan 2009). More surprising is that none of these models explicitly investigate the role of this competition in creating performance heterogeneity, but rather focus on within-firm mechanisms that drive the evolution of resource stocks.

Moreover, these models typically do not assume a resource accumulation process with uncertainty and long-term endogenous investment dynamics, which are core tenets of the RBV (Barney 1986, Dierickx and Cool 1989). Hence, these tenets presumably play an important role in the emergence of sustained performance heterogeneity. Instead, many models in the RBV are based on two-period games, which do not allow for studying resource evolution over longer time-periods (e.g., Lippman and Rumelt 1982, Sutton 1991, Makadok and Barney 2001, Brandenburger and Stuart 2007, Almeida Costa, Cool, and Dierickx 2013). Other models do incorporate longer time horizons, but do not account for resource investments optimizing future value under uncertainty (e.g., Nelson and Winter 1982, Knott et al. 2003, Denrell 2004, Lenox, Rockart, and Lewin 2006, Pacheco-de Almeida and Zemsky 2007, Jacobides et al. 2012, Knudsen, Levinthal, and Winter 2014). In these long-term models, investments are often assumed to be a percentage of profit. Such investment assumptions do not account for the fact that in many situations managers ought to take into account that the more profitable strategy might be to make high up-front investments and reap the benefits later, nor do they account for potential asymmetries between leading and lagging firms in investment incentives.

3 Model

To study the role of competition in creating performance heterogeneity and address some of the limitations of prior models, in this paper I employ a model based on a dynamic game with a Markov-perfect equilibrium (MPE), as set forth in the landmark paper by Ericson and Pakes (1995). This framework does incorporate uncertainty and long-term investment dynamics. It has become one of the major workhorses in industrial organization (IO) economics for studying oligopolistic competition. Notwithstanding its popularity in

IO, this modeling approach has not yet been widely adopted in the strategy literature, even though it is well-suited to study strategic processes such as the competitive dynamics of long-term resource accumulation under uncertainty.

The key attributes of how competitive dynamics evolve in a dynamic game model are:

- In the short run, product market competition in a dynamic game is captured using familiar models of oligopoly such as Cournot, which can incorporate a wide variety of competitive situations and resource characteristics (e.g., Adner and Zemsky 2005, Levinthal and Wu 2010, Jacobides et al. 2012, Almeida Costa et al. 2013, Knudsen et al. 2014).

- Over time, the result of firm investment is characterized by a probability distribution, which captures the fact that resource investments are uncertain due to causal ambiguity (Lippman and Rumelt 1982, Dierickx and Cool 1989).

- The dynamic game has an infinite horizon, requiring firms to continuously re-invest in order to maintain their competitive positions; this captures the path-dependent nature of resource dynamics (Arthur 1989, Selove 2013).

- Investments are endogenous in a dynamic game with MPE, with firms optimizing the long-term net present value (NPV) of their investments. By contrast, models without MPE need to incorporate precise assumptions about the functional form of firms' investment behavior, with their own additional variables and parameters (e.g., Nelson and Winter 1982, Jacobides et al. 2012). Though the MPE model comes with stronger rationality assumptions, a great advantage is the resulting parsimony of the model.

To my knowledge, this is the first model in the strategy literature combining the above core tenets of resource competition into a single model. Specifically, my model is based on the implementation by Besanko and Doraszelski (2004), who employ a two-firm dynamic game without entry and exit. The key elements I add to the model by Besanko and Doraszelski are a direct linkage with the resource-based view, the ability to vary resource characteristics (in particular the extent to which they are scale-free), the analysis of how these characteristics affect firm-specific heterogeneity, and the use of continuous time as outlined in Doraszelski and Judd (2012).

3.1 Assumptions

As is the case with any model, I make several simplifying assumptions. These assumptions are based on two principles. First, where possible they are aligned with models in prior literature, thus helping to create a cumulative body of research. Second, they minimize the number of free parameters, thus helping to keep the model tractable and understandable. More complicated models can easily lead to over-parametrization, raising concerns about the extent to which the results are generalizable over the parameter space (Adner, Polos, Ryall, and Sorenson 2009, p. 205). Following these two principles, the key assumptions of the model are:

- The model includes only two firms. This has been a common assumption in prior models (e.g., Makadok and Barney 2001, Makadok 2001, Besanko and Doraszelski 2004, Adner and Zemsky 2006, Levinthal and Wu 2010, Chatain 2014). Though a strong simplification compared to a many-firm model (potentially with entry and exit), the two-firm model does capture the essence of competition, as it can be regarded as a focal firm competing with its strongest rival.

- In the product market, firms engage in quantity competition with a Nash equilibrium, of which Cournot competition is a special case. It is a workhorse model of competition and has been employed in many prior models (e.g., Besanko and Doraszelski 2004, Denrell 2004, Adner and Zemsky 2005, Lenox et al. 2006, Knudsen et al. 2014), including models of scale-free and non-scale-free capabilities (Levinthal and Wu 2010). Quantity competition is used here instead of price competition, because the latter can lead to very aggressive competitive moves. For instance, in a simple Bertrand model players price at marginal cost, not allowing firms to recuperate sunk cost investments.

- There is only one resource type relevant for production, and this type does not change over time. Also this assumption has been used by several prior models (e.g., Makadok and Barney 2001, Denrell 2004, Jacobides et al. 2012). Some scholars have used two types of resources or capabilities, because they are interested in the interaction across different types (e.g., Makadok 2001, Levinthal and Wu 2010). Since in this paper I am primarily interested in between-firm interaction due to competition and investment dynamics—and not in within-firm interaction across different resource types—I model competition for a single type of resources.

3.2 Resource evolution

The model's fundamental variables are the two firms' resource positions x_1 and x_2, which describe the industry state at each moment in time. These resource positions determine the firms' cost curves, which in turn determine profits through quantity competition. The resource states x_i evolve over time through a combination of depreciation and investment, both of which are stochastic in nature. The investment levels are determined by the MPE, based on the assumption that firms make NPV-optimal decisions.

The model has two sectors: product market competition (in Nash equilibrium) and resource investment dynamics (in Markov-perfect equilibrium), as described below in more detail. Given initial conditions for the resource states x_i, the equilibrium solution leads to a stochastic distribution over all possible resource paths over time $x_i(t)$, which in turn can be used to study the stochastic behavior of any resulting variables, such as investment and profit over time. Figure 1 provides a high-level overview of the model's key variables and their evolution over time.

Insert Figure 1 about here

Below, I will provide a mathematical description of the model. Technicalities are relegated to Appendix A, and further details can be found in the extensive IO literature on this topic (e.g., Ericson and Pakes 1995, Besanko and Doraszelski 2004, Doraszelski and Pakes 2007, Doraszelski and Judd 2012).

3.3 Product market

As mentioned earlier, the product market is based on quantity competition. For simplicity and consistency with earlier papers, I assume a linear demand function. Without loss of generality, the maximum willingness-to-pay can be taken equal to one, and the maximum demand equal to ten. This yields:

$$p(q_1, q_2) = 1 - \frac{q_1 + q_2}{10} \tag{1}$$

The effect of the resource positions is captured in the cost functions, as is common in the literature (e.g., Denrell 2004, Levinthal and Wu 2010, Jacobides et al. 2012). Note that this assumption is primarily made for expositional parsimony; from a strategic perspective there is no fundamental difference between resources affecting willingness-to-pay (such as brands) and those affecting costs (such as production technologies).

As Levinthal and Wu (2010) stipulate, a key characteristic of resources is the extent to which they are scale-free. This scalability of resources determines how they affect firms' marginal cost curves (Levinthal and Wu 2010, p. 785–786). I use a family of logistic functions to model the effect of scalability on marginal cost:

$$mc(q, x) = \frac{1}{1 + \mathrm{e}^{-(q - q_0(x))/S}} \tag{2}$$

In this equation, the scalability parameter $S > 0$ captures the extent to which resources are scale-free.

Insert Figure 2 about here

Figure 2 shows the shape of the marginal cost curves for different levels of resource positions x and scalability S. The right-most chart in the figure shows that when S is large, resources are mostly scale-free, meaning that "the value of resources is assumed to not be reduced as a result of the sheer magnitude of firm operations over which they are applied." (Levinthal and Wu 2010, p. 781). In terms of marginal cost, this means that having more resources x lowers the entire cost curve, largely independent of the quantity produced q. This is analogous to the effect of the scale-free capabilities γ_m in Levinthal and Wu (2010, Equation (1)). Examples of such resources are production technologies and patents.

On the other hand, when S is close to zero, resources have low scalability (i.e., they are non-scale-free), meaning that having more resources x only lowers the marginal cost for some units of production q, until the resources have been depleted (see left-most chart of Figure 2). In other words, using resources with low scalability carries an opportunity cost. The resulting cost function in the limit $S \to 0$ is equivalent to how capacity constraints are modeled in the modern IO literature (Besanko and Doraszelski 2004, p. 27). Examples of such resources are plants, equipment, or personnel (Levinthal and Wu 2010, p. 783).

Note that for any combination of S and q, a firm without resources has marginal cost $mc(q, x = 0) = 1$ and for the maximum number of resources it has $mc(q, x = 10) = 0$. Evidently, a firm with $x = 0$ cannot produce profitably, because no consumer is willing to pay more than the marginal cost of one. For values of the resource position x between 0 and 10, the function $q_0(x)$ is defined such that the maximum total cost reduction is always equal to the number of resources x. In other words, at full production $q = 10$ (which is the maximum demand) a firm's total cost is always $10 - x$, regardless of the resource scalability S. The functional form of $q_0(x)$ is derived in Section A.1 of the appendix.

If firm $i = 1, 2$ has a production quantity of q_i and resource position x_i, its profit is:

$$\pi_i = p(q_1, q_2)\, q_i - \int_0^{q_i} mc(q, x_i)\, \mathrm{d}q \tag{3}$$

$$= p(q_1, q_2)\, q_i - tc(q_i, x_i) \tag{4}$$

The functional form of the total cost $tc(q, x)$ is derived too in Section A.1 of the appendix.

The produced quantities q_i are determined by the Nash equilibrium. This means that the quantity a firm produces is a best response given the other firm's quantity: $q_1 = BR_1(q_2)$ and $q_2 = BR_2(q_1)$. The best response function is defined by setting the derivative of profit with respect to quantity equal to zero. For instance, given x_1 and q_2, Firm 1 chooses its quantity q_1 such that: $\frac{\partial \pi_1}{\partial q_1} = 1 - \frac{1}{10}(2q_1 + q_2) - mc(q_1, x_1) = 0$. As is common in quantity competition with increasing marginal cost, there exists a unique Nash equilibrium (Mas-Colell, Whinston, Green, et al. 1995, p. 395). Thus for a given scalability parameter S, the resource positions x_i determine both firms' quantity choices as well as their resulting profits $\pi_1(x_1, x_2)$ and $\pi_2(x_1, x_2)$. These functions have no closed-form solutions, but can be easily approximated by numerically solving for the fixed point of the function $q \mapsto BR_1(BR_2(q))$ and calculating the profit using Equation (4). Because all assumptions are symmetric between Firm 1 and Firm 2, the solution can be described by one function π equal to the profit of Firm 1:

$$\pi(x_1, x_2) := \pi_1(x_1, x_2) = \pi_2(x_2, x_1) \tag{5}$$

3.4 Investment dynamics

While product market competition determines both firms' profits as a function of their resources x_i at a certain moment in time, the investment dynamics determine the (stochastic) evolution of the resource positions over time. In a dynamic game, the gain rate of a resource as a function of the annual investment $y \geq 0$ is commonly specified using the following functional form (Besanko and Doraszelski 2004, Doraszelski and Judd 2012)[1]:

$$f(y) = \frac{g\,y}{c\,g + y} \tag{6}$$

Over a short period of time Δt, the probability of gaining a resource is $f(y)\Delta t$. Thus, the function $f(y)$ is the resource gain hazard, describing the expected rate of gaining resources per year for a given investment rate y. Clearly, $f(0) = 0$ and f is always increasing in y. For a small investment $y \ll c$, the rate of gaining a resource is approximately y/c, so $c > 0$ parametrizes the minimum average cost of obtaining a resource. For a large investment $y \gg c$, the probability of gaining a resource approaches the maximum growth rate $g > 0$, which reflects the diminishing returns of additional investment in a given time period of fixed duration, and captures the time-compression diseconomies of resource investment (Dierickx and Cool 1989, p. 1507). Thus for low values of g, time-compression diseconomies play a large role, while they become less salient for higher values of the maximum growth rate. Note that for $x = 10$, necessarily $f(y) = 0$ replaces Equation (6), ensuring that firms cannot go beyond the maximum number of resources for which the cost functions are defined.

While resource positions x can improve through investment, they can deteriorate through depreciation. The probability for a firm with x resources to lose a resource through depreciation over a time period Δt is $\delta\, x\, \Delta t$. For instance, $\delta = 0.1$ indicates a depreciation hazard of 0.1 per year per resource, which roughly means that each resource has a 10% probability per year to depreciate (more precisely, the time to resource depreciation follows an exp(0.1) distribution).

The investment policies for a given resource state $y_1(x_1, x_2)$ and $y_2(x_1, x_2)$ are determined by the Markov perfect equilibrium (MPE). In equilibrium, the investment y is defined such that Firm 1's investment policy optimizes its long-term expected value V_1 given the investment policy of Firm 2, and vice versa. Given the symmetry between Firm 1 and Firm

[1]Note that my parametrization is different from the one commonly used by researchers in IO, who use $\alpha = 1/c$ to parametrize investment efficiency, and don't have a separate parameter g.

2, also the investment policies are assumed to be symmetric, so that there is one optimal investment policy function y that needs to be determined: $y(x_1, x_2) := y_1(x_1, x_2) = y_2(x_2, x_1)$. Similarly, there is a single function $V(x_1, x_2)$ to be determined.

The long-term expected value of a resource state (x_1, x_2) is the sum of expected discounted cash flows, for a given discount rate $\rho \in (0, 1)$ and resource evolutions $x(t) = (x_1(t), x_2(t))$ with initial condition $x(0) = (x_1, x_2)$:

$$V(x_1, x_2) = \mathrm{E}_{x(t)} \int_0^\infty \mathrm{e}^{-\rho t} \left[\pi(x(t)) - y(x(t))\right] \mathrm{d}t \tag{7}$$

Solving for the MPE requires dynamic programming, because on the one hand the value function $V(x_1, x_2)$ depends on the distribution of the time evolution $x(t)$, and on the other hand this time evolution $x(t)$ depends on the investment policy $y(x_1, x_2)$ which in turn depends on the expected value function $V(x_1, x_2)$. Albeit somewhat tedious, the solution of the MPE is well-known and is implemented through iterative numerical estimation of the Bellman equation. Details are in Section A.2 of the appendix.

Table 1 provides an overview of all variables in the model and Table 2 of the parameters with their base case values.

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4 Results

The primary goal of this paper is to investigate how long-term investment dynamics shape the evolution of firm-specific heterogeneity, and how industry-specific resource characteristics affect this process. In my model the parameters in Table 2 characterize resources in a given industry. I will start with exploring the role of resource scalability S, and after that investigate the role of the other parameters in shaping performance heterogeneity.

4.1 The effect of scalability on heterogeneity

Figure 3 shows how resource scalability affects the evolution of the joint probability distribution of both firms' resource positions $P(x_1, x_2)$. The three rows represent the evolution for low ($S = 0.1$), moderate ($S = 1$), and high ($S = 10$) resource scalability. The other parameters are equal to the base case values in Table 2. In each of the rows, both firms start with zero resources ($x_i = 0$) at $t = 0$. The columns show how this initial distribution evolves over time. The stationary distribution in the rightmost column is the limiting distribution for $t \to \infty$.[2]

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In all three cases ($S = 0.1, 1, 10$) at least some heterogeneity in resource positions emerges over time due to the uncertainty in resource gain and loss (see Figure 1). Clearly, the more scalable the resources in an industry the larger the heterogeneity becomes over time. Especially for $S = 10$, denoting highly scalable resources, performance differences increase strongly over time.

Figure 4 shows what these probability distributions imply for the evolution profits π of an individual firm. These charts show simulated sample paths of a firm's profit for industries with different levels of resource scalability S. In each of the three charts, a firm starts with $x_{1,2} = 0$ and over time it gains or loses resources according to the probabilities as described in Figure 1 and Equation (6). Total profits are calculated using Equation (4).

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[2]More formally, the stationary distribution is the probability distribution $P(x_1, x_2)$ such that if this were the initial probability distribution at $t = 0$, the probability distribution at each time $t > 0$ would remain the same.

These charts show that also at the level of the individual firm, profits over time are much more heterogeneous when resources are highly scalable. Note that resource positions and firm profits continue to change even when the industry is stationary. As Figure 3 shows, already at $t = 15$ the probability distribution of (x_1, x_2) is close to stationary, while the simulations in Figure 4 are continued well beyond that time, until $t = 100$. This illustrates that "stationary" does not mean that "nothing happens". Firms need to continuously make investments, and can gain or lose any favorable competitive positions—it is only the probability distribution of competitive positions that remains constant, not the positions themselves. Therefore, firm profits will continue to change over time, even in mature industries, capturing an important aspect of business reality.

4.2 How scalability leads to high heterogeneity

Figures 3 and 4 clearly demonstrate that differences in resource positions increase much more in industries with higher resource scalability, leading to more performance heterogeneity. To investigate why this is the case, Figure 5 shows the expected resource gain $f(y)$ as a function of Firm 1's resource advantage $x_1 - x_2$ for different levels of scalability S. The expected values of $f(y)$ are calculated based on the stationary distributions for the different levels of resources scalability, according to the rightmost column in Figure 3. The resource states $x_1 = x_2 = 10$ are excluded, because $f(y) = 0$ in those cases by assumption.

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The graphs in Figure 5 show that for low and moderate levels of resource scalability ($S = 0.1$ or 1) the incentive to invest decreases with an increasing resource advantage. A firm in a disadvantage resource position has an incentive to catch up and will consequently have a higher probability $f(y)\Delta t$ of gaining a resource than the advantaged player. Conversely, for highly scalable resources ($S = 10$) the *advantaged* firm has a higher incentive to invest and thus extend its lead. This leads to an amplification of performance differences: any small differences in resource positions tend to be amplified over time due to differential investment incentives.

This amplification can be quantified by the difference in resource gain probability relative to the difference in resource positions:

$$A = \frac{f(y_1) - f(y_2)}{x_1 - x_2} \tag{8}$$

For $S = 10$ the expected value[3] of A is 0.016 per year per resource. This means that for each resource a firm is ahead of its competitor it will on average have a 1.6% higher probability of gaining a resource due to asymmetric investment efficiencies. In the other two cases A is negative: $A = -0.046$ for $S = 1$ and $A = -0.12$ for $S = 0.01$. In these cases investment incentives attenuate performance differences over time rather than amplify them.

The magnitude of the amplification A appears quite small. The evolution of heterogeneity in Figure 3 illustrates that even such a small amplification A is consequential. Small heterogeneity of resource positions and investment incentives accumulate over time into large heterogeneity of long-term competitive outcomes.

4.3 Other resource characteristics

In addition to the scalability S, other resource characteristics play a role in amplification too, such as the resource cost c, depreciation δ, and time-compression diseconomies parametrized through g.[4] Figure 6 shows the expected value of the amplification A for different combinations of scalability S (rows) and other parameters (columns). Parameters not indicated take the base case values (Table 2). Figure 7 shows the resulting performance heterogeneity. This is defined as the expected value of the profit difference relative to the total profits in

[3]Expectation in the stationary distribution, excluding states $x_1 = x_2 = 10$ (because $f(y) = 0$ by assumption) and $x_1 = x_2$ (because Equation (8) is not well-defined).

[4] Note that the discount rate ρ can be kept constant without loss of generality. For instance, taking $\rho = 0.2$, $\delta = 0.2$, $g = 2$, and $c = 0.05$ leads to the same profit, investment, and stationary state functions as the base case values in Table 2; the evolution is about twice as fast but otherwise exactly the same as well. The choice of ρ can be seen as defining the speed of the passage of time.

the stationary distribution:

$$\frac{\mathrm{E}\,|\pi_1 - \pi_2|}{\mathrm{E}(\pi_1 + \pi_2)} \tag{9}$$

Insert Figures 6 and 7 about here

In the presence of low resource scalability ($S = 0.1$, top row), A is always negative, indicating attenuation of performance differences. For high resource scalability ($S = 10$, top row) the amplification A is always higher than for the corresponding case with low scalability. The same is true for the resulting performance heterogeneity. This shows that the effect of scalability on amplification and performance differences holds across a wide range of specifications.

The leftmost columns in Figures 6 and 7 indicate that heterogeneity increases, too, with increasing resource cost. The mechanism is similar as before: if resources are more expensive, the disadvantaged firm has less incentives to catch up, leading to stronger amplification of performance differences, and thus higher heterogeneity. The only exception is the almost constant amplification for increasing resource cost c with low scalability ($S = 0.1$). The resulting performance heterogeneity still increases somewhat in this case though.

Depreciation, in the middle columns, plays a similar role to resource cost. If resources depreciate faster, firms need to make higher investments to keep their resource levels at par, which is less profitable for a firm with a disadvantaged resource position.

The effect of the maximum growth rate, in the right-most columns, is opposite to that of the other parameters. A higher maximum growth rate g implies lower amplification and heterogeneity. Higher values of g correspond to less salient time-compression diseconomies. Consistent with Dierickx and Cool (1989), this means that resource positions of advantaged firms become harder to defend, leading to lower amplification and heterogeneity.

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The charts in Figure 8 show the evolution of resource heterogeneity in two high-amplification cases. In this figure the base case parameters in Table 2 are changed with high scalability ($S = 10$) and high resource cost ($c = 0.2$, panel a) or high depreciation ($\delta = 0.2$, panel b). Though the amplification A and resulting (relative) performance heterogeneity as indicated in Figures 6 and 7 are very similar in these cases, the time evolution pattern is somewhat different.

Figure 8a shows that high scalability along with high resource cost often leads to a monopoly situation with $x_1 > 0$ and $x_2 = 0$ or vice versa. Once one of the players has secured a monopoly, the other firm has a low incentive to invest in overturning it. There is still a chance though that the competitor gains some resources, in which amplification could work against the once-monopolist and propel its competitor to an advantaged situation.

Figure 8b shows that high scalability along with high depreciation can also lead to a monopoly, but with lower probability than with high resource cost. Even though the amplification A is similar in both cases, the depreciation rate δ also directly affects the accumulation dynamics, making it more likely that a monopolist's favorable resource position depreciates, making a monopoly less likely.

5 Discussion

5.1 Theoretical contributions

The above results suggest that competitive amplification is a key mechanism for the emergence of sustained performance heterogeneity. Differential investments across firms can have a profound impact on shaping performance heterogeneity over time. By contrast, most literature until now had focused on within-firm mechanisms, such as causal ambiguity (Rumelt 1984), strategic factor market intelligence (Makadok and Barney 2001), and complementarity (Adegbesan 2009).

As argued earlier, amplification is related to but distinct from mere accumulation Dierickx and Cool (1989). In the latter perspective, resource and performance heterogeneity emerges because small differences across firms set them on different paths that might not converge due to imitation and substitution barriers. One could think of these as somewhat passive "random walks". On the other hand, amplification results from firms active investments with different incentives. Amplification can sometimes work in the opposite direction of accumulation, for instance in markets with low versus high depreciation (as discussed in the Introduction).

Moreover, the model is based on MPE industry dynamics This framework has received little attention in strategy research so far, while it has several characteristics that make it attractive for strategy research:

1. While in traditional economic models (which are often used in strategy research) the equilibrium is static, the MPE used here is dynamic. As Figure 4 illustrates, competitive positions can continue to change even in the stationary distribution, capturing an important aspect of business reality. For instance, Nike and Reebok were close contenders in the footwear market in the late 1980s; similarly ASML and Nikon both had significant shares of the lithography equipment[5] market in the late 1990s; and Dell and Gateway were once vying for the PC market (Zook 2004). Yet, in each of these markets only one of the established contenders has been able to sustain its success, while the other has faded into oblivion[6]. The MPE can capture this continued flux of competitive positions, because it is an equilibrium in investment policies, while traditionally used equilibrium concepts are in terms of product market decisions (such as price or production quantity), which by definition lead to static outcomes after competitive positions have been established.

[5]Lithography machines are essential equipment for making integrated circuit (IC) chips for computers, smart phones, etc. Today, ASML is the undisputed world market leader in high-end lithography equipment.

[6]Today, Reebok is a brand of Adidas, Nikon's role in the lithography market has been marginalized, and Gateway has been absorbed into Acer.

2. The MPE model can incorporate endogenous investment decisions under uncertainty over many time periods to investigate the accumulation of idiosyncratic resource positions. By contrast, most prior models in the RBV have been based on two-period games, which do not allow for reinvestments (e.g., Lippman and Rumelt 1982, Sutton 1991, Makadok and Barney 2001, Brandenburger and Stuart 2007, Almeida Costa et al. 2013). Other models have incorporated longer time horizons, but did not account for resource investments optimizing future value under uncertainty (e.g., Nelson and Winter 1982, Knott et al. 2003, Denrell 2004, Lenox et al. 2006, Pacheco-de Almeida and Zemsky 2007, Jacobides et al. 2012, Knudsen et al. 2014). The present model is able to combine long-term accumulation dynamics with endogenous investments under uncertainty, which both are critical tenets of competitive dynamics in the RBV (Barney 1986, Dierickx and Cool 1989).

3. The MPE framework allows a parsimonious representation of resource dynamics. The present model has merely four free parameters (the fifth parameter in Table 2 can be fixed without loss of generality, see footnote 4 on page 17). Such parsimony is important in theoretical models because an abundance of free parameters can allow fitting them to match almost any situation, and thus yielding little theoretical insight (Knudsen, Levinthal, and Puranam 2019). Moreover, a parsimonious representation allows a more in-depth investigation of each individual's parameter role.

5.2 Empirical predictions

In addition to the above theoretical predictions, the model makes several empirically testable predictions. Because the level of competitive amplification depends on the resource characteristics in an industry, this results in differences in the level of firm-specific heterogeneity in an industry. Specifically, the results in Figures 6 and 7 translate almost one-to-one into empirical propositions:

1. The higher the *scalability* of resources in an industry, the higher the level of amplifica-

tion and resulting performance heterogeneity.

2. For highly scalable resource, the higher the *sunk cost* of resources in an industry (relative to the potential profits), the higher the level of amplification and resulting performance heterogeneity. For resources with low scalability higher cost does not lead to higher amplification, and has a smaller effect resulting performance heterogeneity.

3. The higher the *depreciation rate* of resources in an industry, the higher the level of amplification and resulting performance heterogeneity.

4. The stronger the *time-compression diseconomies* (corresponding to lower maximum growth rates), the higher the level of amplification and resulting performance heterogeneity.

Such differences could, for instance, be tested using variance decomposition of performance, which includes a firm-specific effect (Rumelt 1991). In fact, there is evidence of significant differences in the size firm-specific effects across markets, geographies, and studies (McGahan and Porter 1997, Vanneste 2017). Some studies have started to explore the sources of these differences, for instance due to macro-economic factors (Bamiatzi, Bozos, Cavusgil, and Hult 2016). The present study suggests that the resource characteristics in an industry and the extent to which they lead to amplification are important other factors to be investigated when analyzing differences in performance heterogeneity across markets.

5.3 Managerial implications

In addition to contributing to the academic literature, this study also has directly relevant managerial implications. For instance, when investing in a new industry, managers need to be aware of the level of amplification to expect depending on the characteristics of the resources they invest in. If amplification is high, it is imperative to make major investments early on to pre-empt potential competitors obtaining an insurmountable lead. In lower-amplification environments, managers can take a less aggressive approach, since an advantaged firm will have a lesser incentive to defend its lead.

The model holds implications for firms in more mature markets too. Particularly, it illustrates the vulnerability of firms even if they have a dominant competitive position. The reason is that dominant competitive positions tend to arise in high-amplification industries, which have propelled the dominant firm in the first place. However, this amplification can boomerang back at the dominant firm in case they happen to face a deteriorating market position while a competitor is successful to break into the market. In that case the amplification mechanism can work against the once-dominant firm and displace it in favor of a competitor.

5.4 Limitations and possible extensions

For reasons outlined in Sections 3.1 and 5.1, I have deliberately kept the model parsimonious. The assumptions follow prior literature to ensure a cumulative interpretation of the results vis-à-vis earlier studies. Nevertheless, these assumptions potentially pose limitations to the generalizability of the findings. These limitations also present research opportunities for the future, as most of them can be easily alleviated within the present modeling framework. For instance:

1. The present model includes two firms, which can be thought of as a focal firm and its best competitor. To more completely capture industry dynamics, this can be extended to a model with more firms as well as entry and exit dynamics (Ericson and Pakes 1995).

2. The model includes competition for a single resource. This can be extended to multiple resources, which can interact with one another in several different ways. For instance, resources can act as substitutes (Barney 1986) or complements (Teece 1986, Adegbesan 2009). Moreover, technological evolution could lead to one set of resources being displaced by another. Additionally, some resources could be fungible into other resources (Levinthal and Wu 2010), or they could create spill-overs. Finally, higher-

order resources could be included, which by themselves cannot be deployed in product markets, but which could help firms create other resources that can directly yield profits (Wibbens 2019).

3. The MPE as presently implemented assumes a rather strong form of forward-looking rationality employed by firms. In particular, a firm is assumed to take into account both its own and its competitor's optimal investment policies in the future when deciding on its own investments. It would be very interesting to explore the implications of alleviating this assumption, for instance by using less rational heuristics and/or lower-dimensional managerial representations (Csaszar and Levinthal 2016).

6 Conclusion

Amplification can play an important role in creating sustained performance heterogeneity. Competitive amplification occurs in markets with resources that are highly scalable, expensive, short-lived, or take a long time to build. These resource characteristics create incentives for an advantaged firm to extend its lead. In markets with high amplification this can even lead to the emergence of monopolies. In low-amplification markets, competitive positions tend to be more stable and performance heterogeneity lower.

A Algebraic derivations

A.1 Marginal cost

For $0 < x < 10$, the total cost function in Equation (4) equals:

$$\begin{aligned}
tc(q,x) &= \int_0^q mc(q',x)\,\mathrm{d}q' \\
&= \int_0^q \frac{1}{1+\mathrm{e}^{-(q'-q_0(x))/S}}\,\mathrm{d}q' \\
&= S\int_{-q_0(x)/S}^{(q-q_0(x))/S} \frac{1}{1+\mathrm{e}^{-z}}\,\mathrm{d}z \\
&= S\log(1+\mathrm{e}^z)\Big|_{z=-q_0(x)/S}^{(q-q_0(x))/S} \\
&= S\log\left(\frac{1+\mathrm{e}^{(q-q_0(x))/S}}{1+\mathrm{e}^{-q_0(x)/S}}\right) \\
&= S\log\left(\frac{1+\mathrm{e}^{-q_0(x)/S}+\mathrm{e}^{-q_0(x)/S}(\mathrm{e}^{q/S}-1)}{1+\mathrm{e}^{-q_0(x)/S}}\right) \\
&= S\log\left(1+\frac{\mathrm{e}^{q/S}-1}{\mathrm{e}^{q_0(x)/S}+1}\right)
\end{aligned}$$

Note the variable transformation in the third step $z := (q' - q_0(x))/S$.

As discussed in the text, the function $q_0(x)$ in Equation (2) is defined such that at full production $q = 10$ the total cost is $tc(10, x) = 10 - x$ irrespective of S. Substituting this in the above equation for the total cost and then solving for $q_0(x)$ yields (still for $0 < x < 10$):

$$q_0(x) = S\log\left(\frac{\mathrm{e}^{10/S}-1}{\mathrm{e}^{(10-x)/S}-1}-1\right) \tag{10}$$

In the boundary cases $x \in \{0, 10\}$, $mc(q, x = 0) = 1$ and $mc(q, x = 10) = 0$ for any combination of q and S, as discussed in the main text.

A.2 MPE calculation

Given the probability rates of gaining a resource through investment (Equation (6)) and of losing a resource through depreciation, the total hazard rate of moving out of the current state $x = (x_1, x_2)$ for a given set of investments y_1, y_2 is the sum of the hazard rates of either player gaining or losing a resource:

$$\phi(x) = f(y_1) + f(y_2) + \delta\, x_1 + \delta\, x_2$$

The Bellman equation optimizing Firm 1's value given an investment policy $y_2(x)$ for Firm 2 is (Doraszelski and Judd 2012, p. 62)[7]:

$$\begin{aligned}\rho\, V(x) &= \max_{y \geq 0} \pi(x) - y + \phi(x)\, [\mathrm{E}_{x'}\, V(x') - V(x)] \\ &= C(x) + \max_{y \geq 0} -y + f(y)\, [V(x_1 + 1, x_2) - V(x)]\end{aligned}$$

The left hand side ρV can be thought of as the opportunity cost of holding a resource position x, which in equilibrium must be equal to the flow of cash plus net value gain under the optimal investment policy, detailed on the first line of the right hand side. The expected value is over the probability distribution of new states x' conditional on a state change occurring, for given investments $y_1 = y$ and $y_2 = y_2(x)$. For instance, conditional on a change state, the probability of Firm 1 gaining a resource is $f(y)/\phi(x)$.

The second line takes out all terms that are independent of y into a single constant $C(x)$ that is irrelevant for calculating the optimal investment policy $y(x)$. This policy follows from taking the first order condition, i.e. setting the derivate $\partial/\partial y$ of the maximand to zero. Defining $\Delta V(x) := V(x_1 + 1, x_2) - V(x)$, this gives $f'(y)\Delta V(x) = 1$. Using the derivative $f'(y) = cg^2/(cg + y)^2$ then yields, for $\Delta V(x) > c > 0$:

$$y(x) = g\left(\sqrt{c\,\Delta V(x)} - c\right)$$

And $y(x) = 0$ for $\Delta V(x) \leq c$.

[7] Note that Doraszelski and Judd (2012) denote the resource state x with ω and the investment y with X. Moreover, they use π for the profit net of investments, corresponding with $\pi - y$ in this paper.

This equation is used to update the optimal investment policy for a given $V(x)$, while this new estimate of $y(x)$ is in turn used to calculate a new approximation of the value function, using (Doraszelski and Judd 2012, p. 68):

$$V(x) \leftarrow \frac{\pi(x) - y(x) + \phi(x)\,\mathrm{E}_{x'}\,V(x')}{\rho + \phi(x)}$$

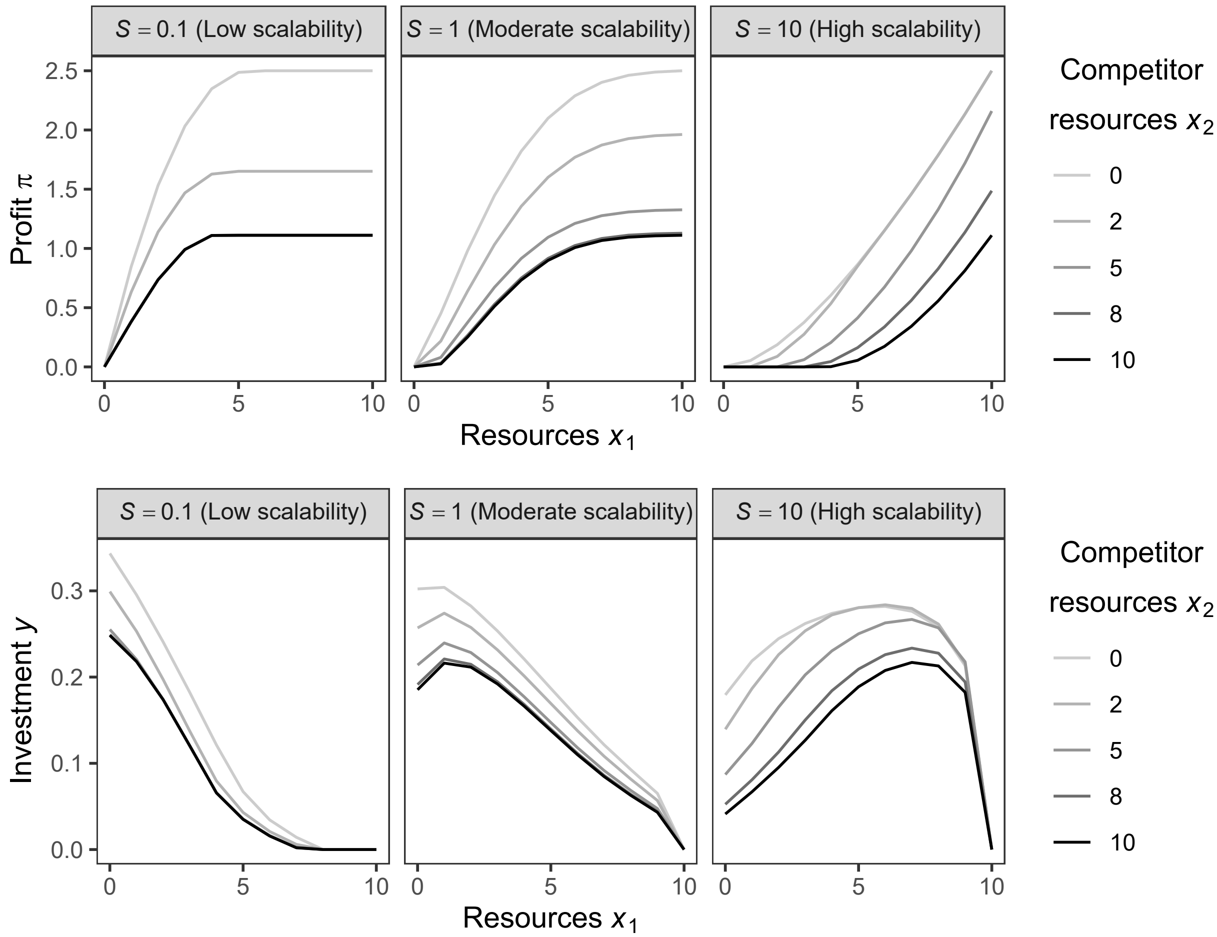
To aid convergence, a weighted average of the previous and the new estimate is used for $V(x)$ in each iteration.

This iterative procedure is implemented in R, using tibbles from the `dplyr` package to store functions of the state space (x_1, x_2) on a grid of integer resource positions $x_i = 0, 1, 2, \ldots, 10$. Thus, functions of the state space such as the equilibrium output q_i, price p, and resulting profits π_i are stored as vectors of length 121 (the square of 11 possible resource positions for each firm), as are the MPE intermediate calculations and outcomes such as the value V, investment y, and state gain hazard rates f.

In general, though existence of the equilibrium is guaranteed, uniqueness is not—but in practice the symmetric MPE usually is unique (Besanko and Doraszelski 2004, p. 30). I tested this myself using random initial conditions, which always led to the same equilibria. Convergence is rapid using modern computing equipment.

As discussed in the main text, though somewhat tedious, the above derivations are standard and closely follow standing practice in IO. See for instance Besanko and Doraszelski (2004), Doraszelski and Pakes (2007), and Doraszelski and Judd (2012), which also contain further technical details.

Below are charts of the resulting profit $\pi = \pi_1$ and optimal investment $y = y_1$ as a function of a focal firm's own resource position (x_1) and its competitor's (x_2). The profit function is a result of the Nash equilibrium in quantity competition, and the investment function of the Markov perfect equilibrium (MPE) as described above, using the base case parameters in Table 2 and the scalability S as specified above the chart.


S = 0.1 (Low scalability)
S = 1 (Moderate scalability)
S = 10 (High scalability)
Profit π
Investment y
Resources x1
Competitor resources x2
0
2
5
8
10
2.5
2.0
1.5
1.0
0.5
0.0
0.3
0.2
0.1

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Tables and figures

Table 1: Model variables

x_i	Resource position of Firm i
q_i	Production quantity of Firm i
π	Profit rate Firm 1†
V	State value for Firm 1†
y	Investment rate Firm 1†
$f(y)$	Resource gain rate function for Firm 1†

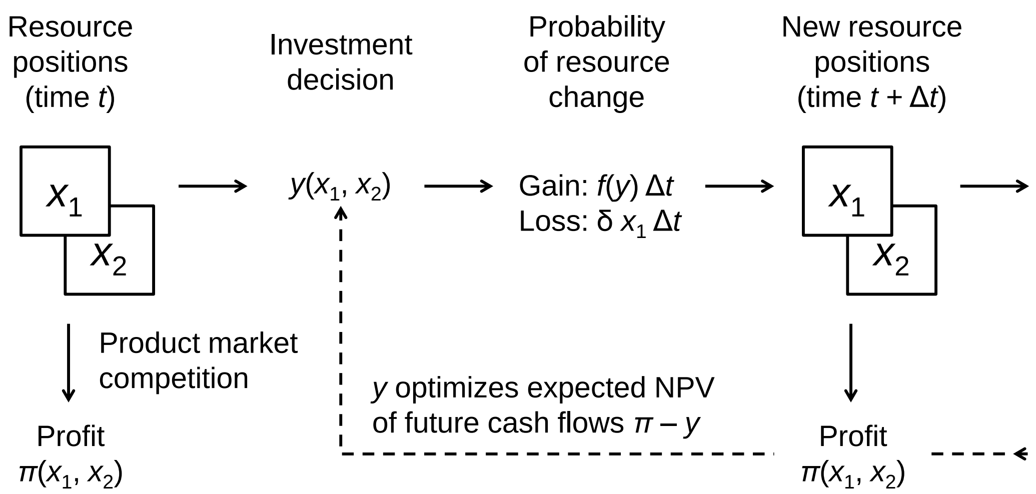
†Functions defined for Firm 1 are symmetrically defined for Firm 2, e.g. $\pi(x_1, x_2) = \pi_1(x_1, x_2) = \pi_2(x_2, x_1)$.

Table 2: Model parameters and base case values

S	1	Scalability parameter
δ	0.1	Depreciation rate
c	0.1	Minimum resource cost
g	1	Maximum growth rate
ρ	0.1	Discount rate

Note. The "rate" parameters are defined per unit of time, e.g. a year. For instance, $\delta = 0.1$ corresponds to an expected depreciation rate of 10% per year.

Figure 1: Resource evolution



Note. Schematic depiction of resource evolution in the model for a focal firm with resource state x_1 and its competitor's state x_2, over a short time period Δt. The variable π denotes the profit rate, y the investment rate, $f(y)$ the gain rate function, and δ the depreciation rate.

Figure 2: Marginal cost functions for different levels of resource scalability S

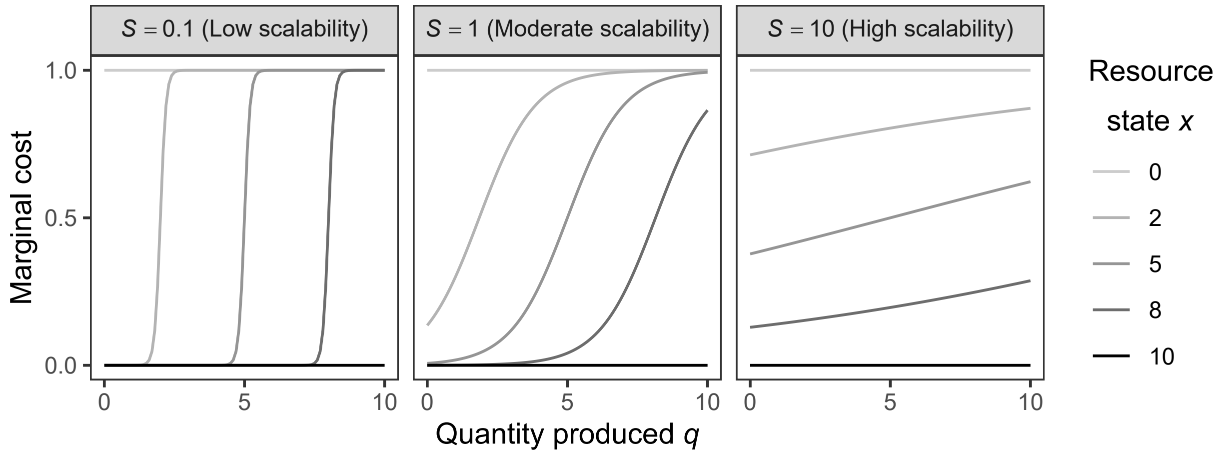
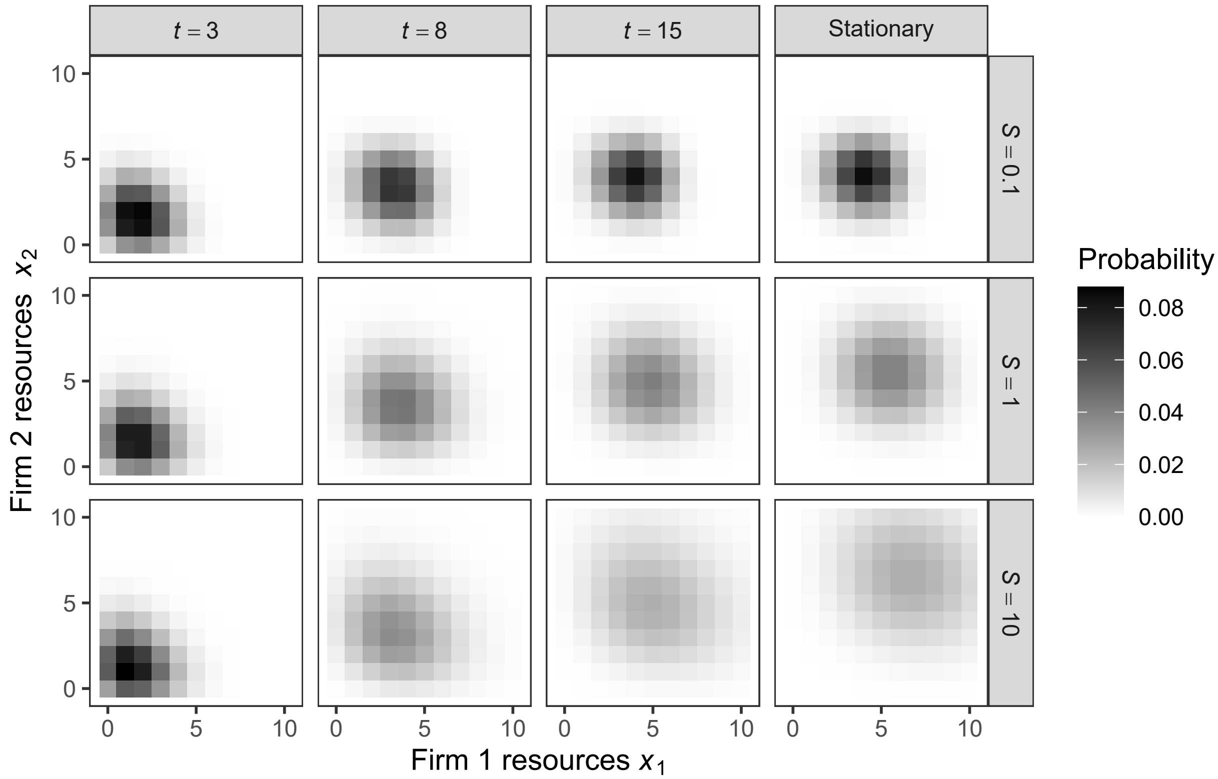
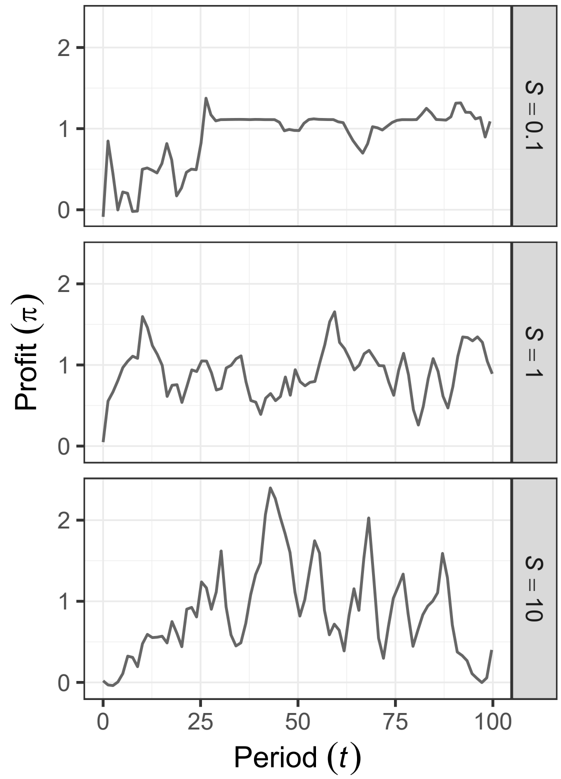


Figure 3: Evolution of probability distribution



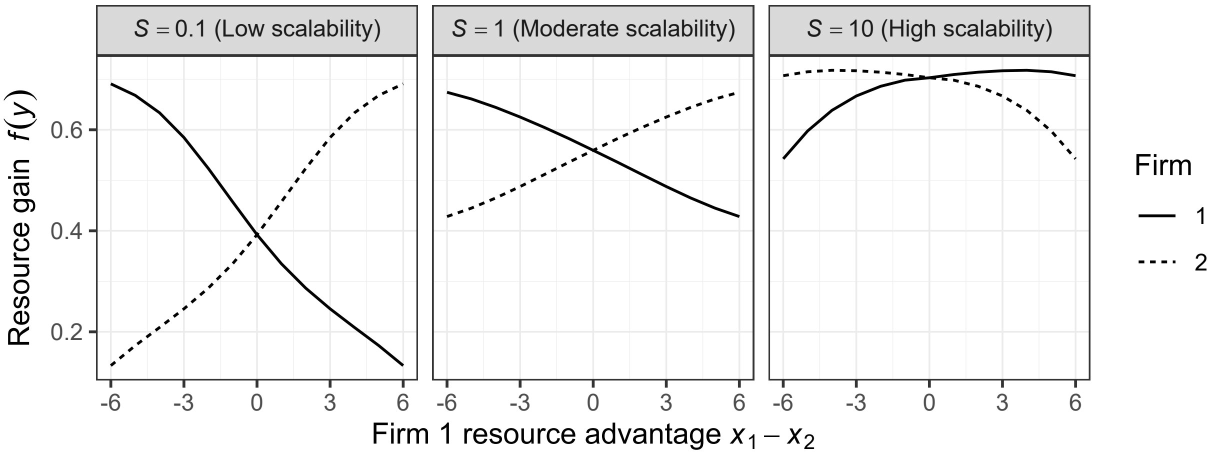
Note. Time evolution of the probability distribution of resource states $P(x_1, x_2)$. The rows represent the evolution for low ($S = 0.1$), medium ($S = 1$), and high ($S = 10$) resource scalability. Other parameters as in Table 2. The stationary distribution represents the probability distribution for $t \to \infty$.

Figure 4: Sample paths of firm profit



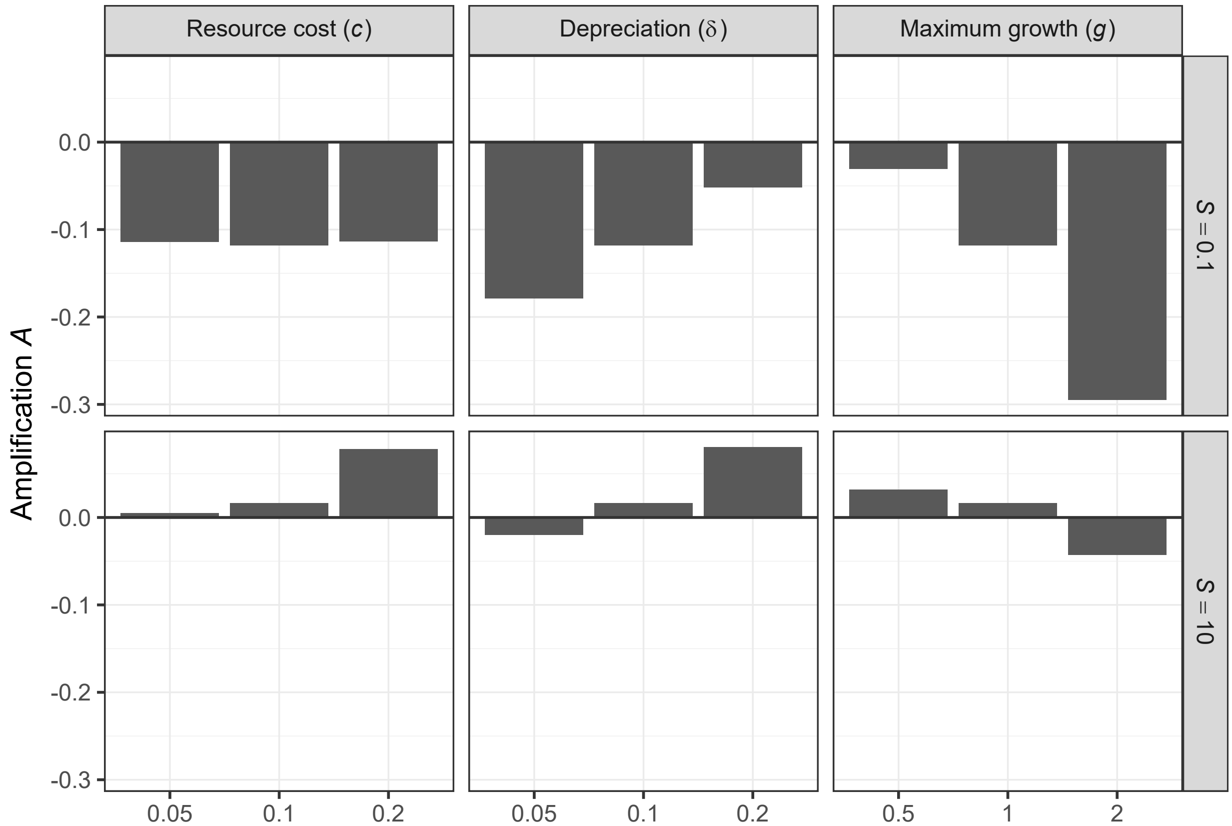
Note. Simulated smoothed evolution of profits over time for a firm participating in an industry with different levels of resource scalability S.

Figure 5: Investment incentives as a function of resource advantage



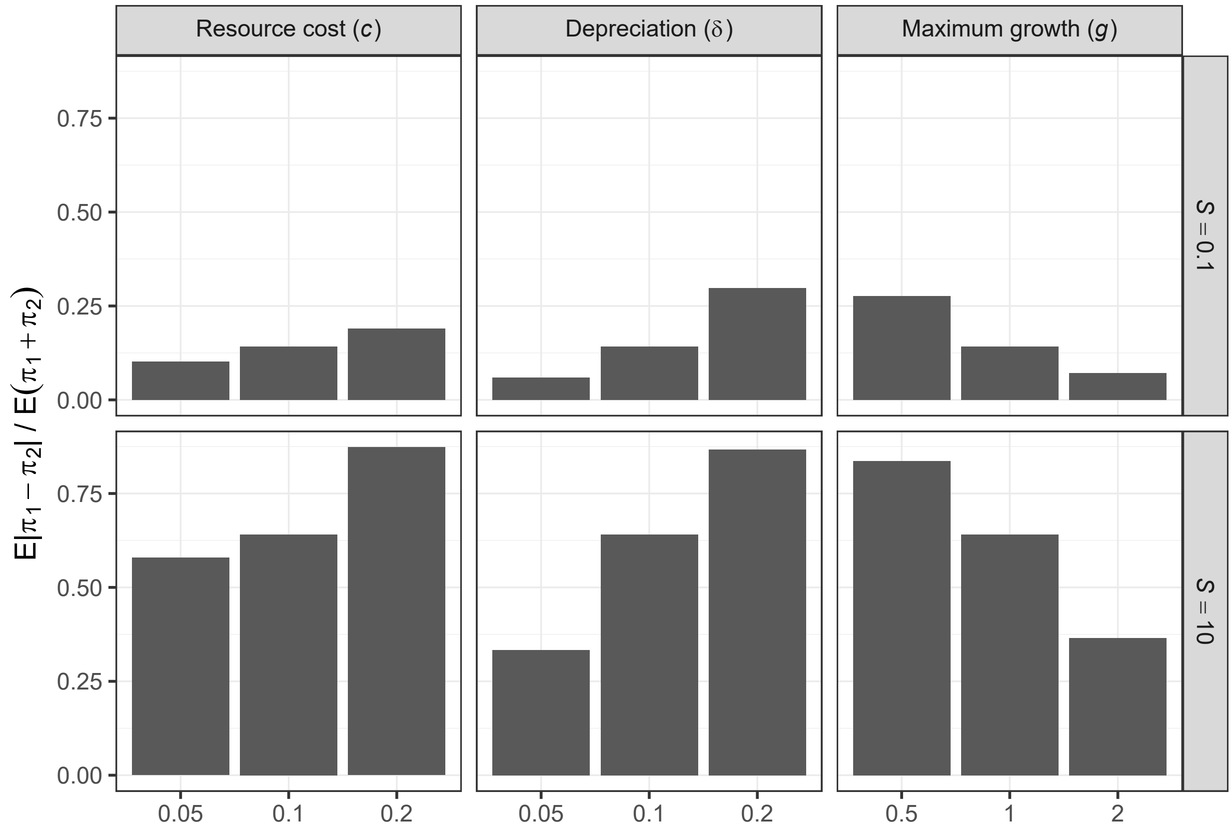
Note. Expected resource gain $f(y)$ as a function of Firm 1's resource advantage $x_1 - x_2$ for different levels of scalability S. The expected values of $f(y)$ are calculated based on the stationary probability distributions for the different levels of resources scalability, according to the rightmost column in Figure 3. The resource states $x_1 = x_2 = 10$ are excluded, because $f(y) = 0$ in those cases, by assumption.

Figure 6: Amplification for different resource characteristics



Note. Amplification $A = \frac{f(y_1)-f(y_2)}{x_1-x_2}$ for different combinations of scalability S (rows) and other parameters (columns). Parameters not indicated take the base case values (Table 2).

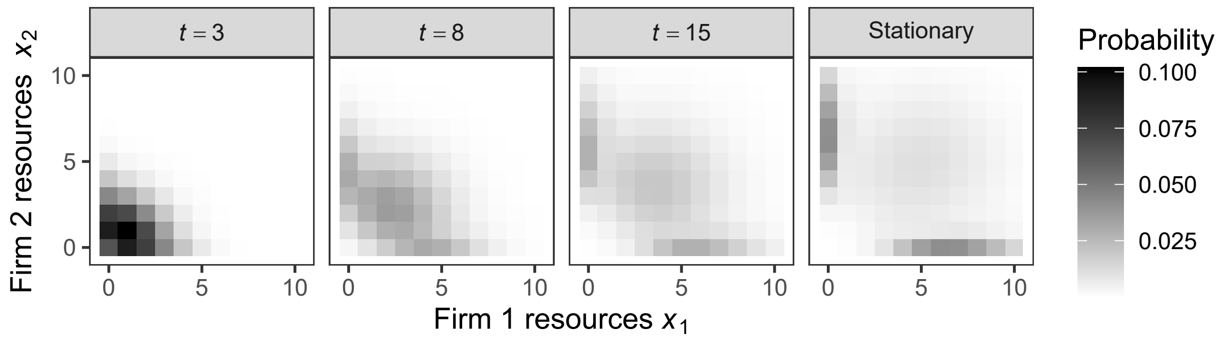
Figure 7: Performance heterogeneity for different resource characteristics



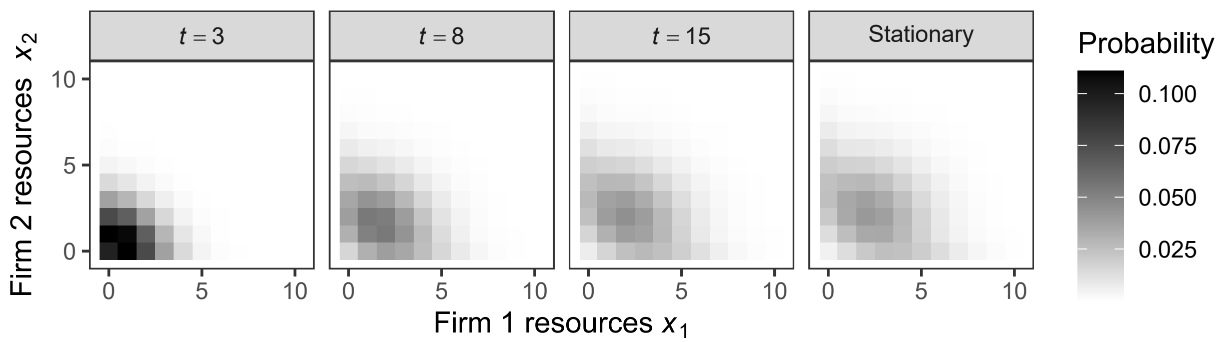
Note. Performance heterogeneity for different combinations of scalability S (rows) and other parameters (columns). Parameters not indicated take the base case values (Table 2).

Figure 8: Evolution of resource positions with high amplification

a. High scalability ($S = 10$), high resource cost ($c = 0.2$)



b. High scalability ($S = 10$), high depreciation ($\delta = 0.2$)



Note. Evolution of resource positions when changing the base case parameters in Table 2 with high scalability and high resource cost (panel a) or high depreciation (panel b).