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Determining reverse salient types and evolutionary dynamics of technology systems with performance disparities

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ABSTRACT

Technological system evolution is marked by the uneven evolution of constituent sub-systems. Subsequently, system evolution is hampered by the resulting state of unevenness, or reverse salience, which results from the presence of the sub-system that delivers the lowest level of performance with respect to other sub-systems, namely, the reverse salient. In this paper, we develop absolute and proportional performance gap measures of reverse salience and, in turn, derive a typology of reverse salients that distinguishes alternative dynamics of change in the evolving system. We subsequently demonstrate the applicability of the measures and the typology through an illustrative empirical study of the PC (personal computer) technological system that functions as a gaming platform. Our empirical analysis demonstrates that patterns of temporal dynamics can be distinguished with the measurement of reverse salience, and that distinct paths of technological system evolution can be identified as different types of reverse salients emerge over time.

Keywords: technological system; system dynamics; reverse salient; computer games

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Introduction

The evolution of a given technological system is hindered by performance imbalances that exist among the sub-systems which comprise that system (Hughes 1983; Rosenberg 1976; Sahal 1981; Constant 1980; den Hond 1998). In this state of affairs, the level of technological performance delivered by the technological system compromises the sub-system that delivers the lowest level of performance among all sub-systems, namely, the reverse salient (Hughes 1983, 1987). Because the performance of the system can be further enhanced by improving the reverse salient through greater utilisation of its performance potential, the reverse salient emerges as a focusing device for technological development (Rosenberg 1969). The dynamics of system evolution is, in turn, reflected in the evolution of the disparity that exists between the performance of the reverse salient and its performance potential. This performance disparity, in other words, the magnitude of reverse salience, emerges as an informative parameter in understanding the evolution of technological systems, because it signifies the system’s limited level of performance. The literature on technological system evolution is nevertheless limited with respect to analytical tools that measure the state of reverse salience (Hugh, Roche and Bennett 2007). In one of the few studies considering measurement issues, Dedehayir and Mäkinen (2008) propose an absolute performance gap measure of reverse salience magnitude. However, such a measure considers only the disparity between sub-systems and remains inadequate in taking into account their heterogeneous levels of technological development. In addition to the absolute measure, this paper therefore proposes a proportional measure of reverse salience, which determines the ratio of the absolute performance gap with respect to the highest level of performance attainable by the technological system. Together, the absolute and proportional measures inform of the temporal change in the performance differential between sub-systems, and at the same time denote the dynamics of change of the system as a whole. Furthermore, by analysing the changes in these measures it becomes possible to derive different types of reverse salients, which denote particular dynamics in technological system evolution. The structure of the paper is as follows. We first discuss technological systems and their general properties, and reverse salients as inherent elements of these systems. Further, we develop absolute and proportional performance gap measures of reverse salience, and then derive a typology of reverse salients with respect to these measures. The empirical illustration, in turn, applies the measures of reverse salience and the typology of reverse salients in the analysis of the PC (personal computer) technological system. The empirical study considers two systemic contexts: the first studying the evolution of the PC game and CPU (central processing unit) sub-systems, and the second studying the PC game and GPU (graphics processing unit) sub-systems. Finally, we conclude the paper with a discussion offering both scholarly and managerial implications along with thoughts on avenues for future research.

Theoretical background

Technological systems

A number of different studies have adopted a systemic view of technology to reveal the complexities that underlie the development of these technologies. For example, studies of the aeroplane (Vincenti 1994; Constant 1987; Tushman and Murmann 1998), electricity supply (Hughes 1983), the automobile (Abernathy and Clark 1985; Clark 1985) and the PC (Christensen 1997; Wade 1995; Christensen and Suarez 1998; Esposito and Mastroianni 1998), all illustrate the technological system as a structured composition of technological parts or sub-systems. Moreover, all of these
technological systems exhibit a number of properties that stem from general systems theory (Skyttner 2001; Simon 1962; von Bertalanffy 1969). First, the technological system has a hierarchically nested structure, whereby the system is seen as a composition of smaller sub-systems (i.e. the system level technology comprises lower level, sub-system technologies) that are themselves systems comprising further sub-systems, and so on (Tushman and Murmann 1998; Murmann and Frenken 2006). For instance, the aeroplane technological system has some major sub-systems including the engine, which is composed of smaller sub-systems, such as the compressor, combustion system and turbine, which are subsequently divisible yet again into smaller sub-systems (e.g. Constant 1987). Second, the sub-systems that are specialised for particular functions are interdependent both within the same, as well as across, different levels of the system hierarchy (e.g. Tushman and Murmann 1998). In this manner, the PC system’s HDD (hard disc drive), CPU and software sub-systems, for example, are interconnected and influence one another (e.g. Christensen 1997). Third, the system and its properties are synthesised through the sub-systems that constitute it (e.g. Tushman and Murmann 1998). Subsequently, the electricity supply system may be analysed through the study of the capacitance, transmission lines and electric generator sub-systems, the performances of which are synthesised at the system level to enable the distribution of electricity (Hughes 1983). Finally, the technological system as a whole is goal-seeking (Hughes 1983; Sahal 1981; Hughes 1987). In this light, the electric supply system has been shown to develop over time to satisfy the objective of increasing the area of electricity distribution (e.g. Hughes 1983), the PC system to increase computational power (e.g. Christensen 1997) and the aeroplane to increase flight velocity (e.g. Sahal 1981). Since the technological system is goal-seeking, it evolves to improve its existing performance output over time. The evolution of the system is nevertheless dependent on the development of all the nested sub-systems (Hughes 1983; Rosenberg 1976; Tushman and Murmann 1998; Murmann and Frenken 2006). In this collective evolution, differences in the rates of development of these interdependent sub-systems, however, lead to the appearance of technological imbalances (Rosenberg 1976; Krell 1992). In the resulting state of technological disequilibrium, the system level performance is significantly limited because of the presence of a sub-system that delivers the lowest level of performance with respect to all other sub-systems, referred to as the reverse salient (Hughes 1983).

Reverse salients

According to Hughes (1983), in its military origin, the reverse salient pinpoints that section of a moving battle line which trails behind all other sections with respect to the overall direction of movement, and subsequently hinders collective forward movement. In the context of evolving technological systems, analogous to the military depiction, the reverse salient denotes a subsystem that delivers the lowest level of performance with respect to all other sub-systems, and at the same time hinders the system level performance delivery. This circumstance arises, first, from the interdependence between sub-systems, whereby the inability of the reverse salient to utilise the performance potential provisioned by other sub-systems creates a technological imbalance. In turn, the synthesis of the sub-systems’ performances, in otherwords the system level performance, is inhibited by the imbalance brought about by the reverse salient. A number of studies in the literature illustrate reverse salients which have impacted the system level performance in this manner. These include, for example, the motor and capacitor sub-systems of the early direct-current electric system that inhibited the efficient distribution of electricity beyond a certain range (Hughes 1983), the gyroscope sub-system of the ballistic missile technological system that limited the
accuracy of missiles (MacKenzie 1987), and the method of transferring digitally created text and image data between different processes that constrained the development of the computer-integrated manufacturing (CIM) system (Hardstone 2004). However, examples, such as the music copyright managing institutions of the mobile music technological system, which curbed the proliferation of mobile music throughout the enduser markets in Japan and Korea (Takeishi and Lee 2005) also show that reverse salients may be more than technical sub-systems. The heterogeneity of these examples, therefore, underlines the diversity of reverse salients, which can be identified in a variety of technological systems. Furthermore, these illustrations highlight not only the impact of reverse salients on the system level performance, but also the incapacity of the reverse salient to utilise the performance potential provisioned by interdependent sub-systems. More specifically, the reverse salient strays behind the sub-system that provisions the highest level of technological performance, namely the technological performance frontier (Dosi 1982), failing to fully utilise the performance potential that it provides. As a result, the presence of a reverse salient gives rise to the unevenness formed by this sub-system’s backward protrusion. As illustrated by Dedehayir and Mäkinen (2008), the magnitude of unevenness, or reverse salience, can be measured as the technological performance disparity between the technological performance frontier and the reverse salient. This absolute performance gap measure, together with the level of performance delivered by the reverse salient, informs of the level of performance that is delivered, as well as the performance potential that remains unutilised by the technological system. While this absolute measure can, subsequently, denote the system level dynamics, it nevertheless ignores the levels of performance attained by the sub-systems. In this paper, we therefore propose that reverse salience can additionally be measured as the proportion of the absolute performance gap with respect to the performance delivered by the technological performance frontier. This proportional measure, importantly, allows the comparison of system development at different points in time, taking into account the absolute level of technological evolution across sub-systems. As a consequence, the absolute and proportional performance gap measures, taken together, provide more comprehensive information about the system level development.

**A typology of reverse salients**

Because the performance of the technological system can be further enhanced by improving the reverse salient through greater utilisation of its performance potential, the reverse salient emerges as a focusing device for technological development (Rosenberg 1969). Hence, the system’s technological evolution is driven by a compulsive necessity to reduce the technological imbalance (Rosenberg 1976; Sahal 1985; Nelson and Winter 1977), where the most fruitful reduction is brought about by the improvement of the reverse salient. The dynamics of change of the technological system can therefore be observed through the temporal change in reverse salience. As a consequence, system dynamics is reliant on the rates of development of both the reverse salient and the technological performance frontier. In this manner, the technological performance frontier can undergo performance increase, experience no performance change at all, or in certain peculiar circumstances, undergo performance decrease, caused, for example, by excessive system complexity or shock from the institutional environment. At the same time, the reverse salient experiences a rate of performance development that is faster, the same, or slower than the rate of change of the technological performance frontier. Consequently, the magnitude of reverse salience, when measured as absolute performance gap, can increase or decrease in relation to the technological performance frontier. At the same time, the magnitude of proportional performance gap can also
increase or decrease in relation to the technological performance frontier. We can, as a result, identify changes in reverse salience according to the absolute and proportional measures, as illustrated in Figure 1. From the changes in the two measures of reverse salience, we can derive four alternative types of reverse salients, as depicted in Figure 1. Of these, the prohibitive reverse salient, first, experiences a substantially lower rate of technological development in comparison with the development of the technological performance frontier. It therefore brings about an increase in reverse salience, measured both in absolute and proportional terms. A prohibitive reverse salient can, for example, denote a constraint that remains unrecognised as a hindrance and therefore lies dormant and unnoticed for a period of time (Moors and Vergragt 2002; Moors 2006).

![Figure 1. A typology of reverse salients.](image)

Moreover, the continuation of its limited development can result in significant limitations to the technological system's progress toward existing system level objectives. Second, the intermediating reverse salient is characterised by a rate of development that is slower than the rate of change at the technological performance frontier, thus resulting in absolute performance gap increase. Nevertheless, the reverse salient evolves at a sufficient pace to reduce the proportional performance gap, even though the absolute gap persists over time. The simultaneous occurrence of absolute performance gap increase and proportional performance gap decrease, however, represents a narrow range of evolutionary possibilities, rendering this state volatile. At the same time, the intermediating reverse salient denotes the system dynamics in between relatively more stable states, such as when there is decrease or increase in both the absolute and proportional measures. As a consequence, this reverse salient type may be observed when some instability is induced into the system, for example, through exogenous factors such as regulatory restrictions or initiatives concerning technological development (Pilkington 1998). Nevertheless, the intermediating reverse salient type promotes system development within the existing regime. The progressive reverse salient, in turn, demonstrates a higher rate of technological development in comparison to the development of the technological performance frontier, thereby leading to a decrease in both the absolute and proportional performance gaps. The reverse salient's pace of technological change may be sponsored by a sub-system industry in which organisations competitively utilise the available
level of technology in developing products that offer higher performance (Zahra and Covin 1993; Das and Van de Ven 2000). Product competition may subsequently push the delivered technological performance level of the reverse salient even higher, also in relation to the technological performance frontier. As a result, the progressive change of this reverse salient leads to closure of the technological performance disparity and therefore enhanced level of utilisation of the reverse salient’s performance potential. Finally, the reorienting reverse salient is characterised by a rate of development that is faster than the rate of change at the technological performance frontier, thus resulting in absolute performance gap decrease. Nevertheless, the reverse salient evolves at a pace that is slow enough to increase the proportional performance gap concurrently. This temporal change in reverse salience may arise from discontinuities in the technological performance frontier, sourced, for example, from disruptive changes (Christensen 1997) within the system or shocks from the institutional environment (Anderson and Tushman 1990). This also may represent new performance parameters rendering the current parameter obsolete or less meaningful. In comparison with the intermediating reverse salient type, the emergence of a reorienting reverse salient represents a fundamental change within the system, which may cause the reorientation of system level objectives and therefore a shift in the critical parameters for technological development.

**Method**

Our method of system analysis measures the magnitude of reverse salience between central subsystems which contribute to the system level performance. The evolution of the technological system is in turn studied through the changing magnitude of reverse salience between sub-systems. We therefore begin our method of analysis by developing the analytical measures of reverse salience. In this effort, we first consider the evolution of any technological sub-system, that, when measured quantitatively by the changes in its technological performance indicator over time (Sahal 1981), produces an S-curve (e.g. Christensen 1992; Foster 1986; Fisher and Pry 1971; Andersen 1999). Second, we derive the measure of reverse salience magnitude by superimposing the technological evolution curves of sub-systems upon a common set of axes, thus creating the basis for two – absolute and proportional – measures of reverse salience (see Figure 2). The dashed line in Figure 2 represents the actual level of technological performance delivered by the reverse salient sub-system over time. The solid line, in comparison, denotes the evolution of the technological performance frontier. Thus, the solid line represents the potential level of technological performance provisioned to the reverse salient across this timeframe. The gap between the two technological development lines represents the changing magnitude of reverse salience over time. First, at any point in time, the magnitude of reverse salience can be measured as absolute performance gap by calculating the vertical separation of the lines at that point in time, denoted in Figure 2 by $\Delta p t_1$ and $\Delta p t_2$, at time $t_1$ and $t_2$, respectively. The absolute performance gap measure indicates how far the reverse salient is behind the technological performance frontier, although it does not reflect the reverse salient’s impact on system level performance. In particular, the absolute measure does not take into account the level of technological evolution across different sub-systems, at different points in time.
On the contrary, the technological system performance is better reflected in the proportion of the technological frontier performance that is yet to be utilised by the reverse salient. Therefore, the magnitude of reverse salience is, second, measured as proportional performance gap, which is evaluated as the ratio of the absolute performance gap with respect to the performance at the technological frontier at a particular point in time. The proportional measures of reverse salience are indicated in Figure 2 as \( \frac{\Delta p_t}{p_t} \) at time \( t_1 \), and \( \frac{\Delta p_t}{p_t} \) at time \( t_2 \), respectively. It is, in turn, possible to measure the changes in reverse salience magnitude as absolute performance gap (\( \frac{\Delta p_t}{p_t} - \frac{\Delta p_t}{p_t} \) in Figure 2) and proportional performance gap (\( \frac{\Delta p_t}{p_t} - \frac{\Delta p_t}{p_t} \) in Figure 2), over a particular period of time (\( t_2 - t_1 \) in Figure 2). Moreover, the analysis of the temporal change in reverse salience allows the evaluation of an increase or decrease in the absolute and proportional performance gap measures. Subsequently, by comparing the changes (whether increase or decrease) in the absolute and proportional performance gaps within the given period of time, it is possible to derive the type of reverse salient (see Figure 1) that persists across this particular time span. Further, the shifts from one reverse salient type to another can inform us of the developments at the system level and its overall dynamics.

**The technological system**

Our empirical work illustrates the applicability of the absolute and proportional measures of reverse salience in the analysis of an evolving technological system, and the identification of reverse salient types from the observed changes in reverse salience. In our empirical illustration we have analysed the PC technological system, focusing specifically on its function as a computer gaming platform. We have selected this empirical setting, first, on the basis of the PC system’s continuous endeavour to deliver higher levels of computer gaming performance. Second, while computer gaming on the PC technological system has evolved over the years, disparities have been observed in the performance...
levels of its sub-systems, namely, the PC hardware and PC game software technologies. Third, the hardware and software sub-systems are interdependent, as illustrated by the minimum hardware performance required by the PC game software in order to deliver gaming performance on the PC technological system, whereby higher minimum hardware requirements denote higher levels of overall system performance for gaming purposes. The significance of the PC as a platform for computer gaming since the 1990s (Hayes and Dinsey 1995; Poole 2004), together with the highly dynamic nature of the sub-systems’ technological evolutions, subsequently provides a rich setting with continuously changing performance disparities. The combination of these factors, therefore, makes the PC technological system informative for illustrating our measures of reverse salience and typology of reverse salients. In our study, the PC represents the system level of a hierarchically structured technological system, which evolves over time to deliver better gaming performance to the end-user. By gaming performance, we refer, for example, to the video qualities (e.g. polygon rendering) that materialise on the PC during game play, although in our study we do not attempt to measure these aspects. Rather, we consider the technical performance of the PC’s hardware and software sub-system technologies, which enables the delivery of system level qualities. We additionally recognise that the evolution of these technologies is brought about by the strategic actions of firms in their respective industries. Game developers, in particular, consider factors such as potential markets and the compatibility of their technologies with complementary hardware technologies. In this manner, these firms attempt to reconcile the highest level of technology that can be embedded in the game design and the level of game technology that can actually be supported by the hardware that is available in the market. Rather than considering all sub-systems that constitute the highly complex PC system, our analysis has concentrated on the most central technical sub-systems for gaming performance. In this manner, we have studied the technological evolution of sub-systems, whereby one central sub-system utilises the technological performance provisioned by another, to reflect the evolution of gaming performance that is delivered at the system level. The illustrative empirical study has therefore analysed the PC game software sub-system and its co-evolution with two important and interdependent hardware sub-systems: the CPU and GPU. However, in order to limit our study we have defined the system under analysis to include only two sub-systems. In our first system definition, we have included and analysed the CPU and PC game sub-systems, and in the second, we have included and analysed the GPU and PC game sub-systems. The system definitions are important because the reverse salient can only be identified with respect to a technological system that is defined a priori. Consequently, the reverse salient must be a subsystem that lies within the system’s boundary and not one that is excluded from the system as an object under study. In this manner, exogenous factors may be antecedents of reverse salients, but not reverse salients themselves. This further suggests that the reverse salient can be identified only relative to a specific context, such that different reverse salients may be identified in alternative contexts.1 In our analysis, the CPU is a central hardware component of the PC which is specialised to interact with other components (e.g. hardware and software), to process data and enable the Q1 computational performance of the computer. The GPU, on the other hand, is specialised for the graphics performance (qualitative aspects of the image on a display) of the PC in software applications, and takes some of the processing responsibility away from the CPU for this purpose. The PC game software, in turn, provides the instruction set that is processed by the CPU and GPU to translate the data into the gaming performance made available on the PC. The centrality and interdependence of these sub-systems for computer gaming is, further, made apparent from the
software developers’ stipulation of performance requirements, specifically for the CPU and GPU components, to ensure the functionality of their software.

**Technological performance indicators**

For each of these nested sub-systems we selected technological performance indicators that allow the analysis of performance evolution and the measurement of reverse salience. While the performance of the CPU can be measured along different dimensions (for example, MIPS – millions of instructions per second – number of transistors, bus bandwidth), we have selected the performance indicator of processing speed, operationalised in this paper as the clock speed of the processor (in Hertz [Hz]). The processor speed indicates the CPU’s speed of operation, governing the computational performance of the PC through its interaction with software programs such as PC games. Higher speeds mean faster data manipulation and increased computer performance, resulting in enhanced gaming performance at the system level. This is the most appropriate performance indicator used in our analysis, because it is the central performance parameter stipulated by game developers and publishers for game functionality. Similarly, while the performance of the GPU can be measured along different dimensions, the graphics memory, measured in megabytes (MB), is the central indicator stipulated by game developers and publishers for game functionality, and is for this reason considered in our study. The graphics memory denotes the GPU’s ability to store and make available graphics data to the PC. Larger memory capacity means increased computer graphics performance, resulting in enhanced gaming performance delivered at the system level. For the PC game sub-system we have considered that the software is designed to utilise a certain level of hardware performance. For this reason, the game software stipulates a set of minimum hardware performance requirements with which the software will function as designed. However, the game software can additionally be designed to deliver a higher level of gaming experience, for example by making additional game features accessible during game play (i.e. recommended specifications). Nevertheless, in our study we have focused only on the functional performance of the hardware and software sub-systems, and not on the additional gaming experience that may be delivered by these sub-systems. We have therefore used the minimum hardware requirement stipulated by the software as the technological performance indicator to study the PC game subsystem’s evolution. In this manner, we identify a particular PC game software as bearing a higher level of technological performance than another software, when its stipulated minimum hardware requirement is higher than that of the latter. This is because a PC game that requires a higher level of hardware performance will utilise a greater amount of hardware capacity to function, and, in turn, enable the delivery of a higher level of gaming performance at the system level.

**The data**

We collected data on CPU processor speeds from processor performance databases found on the Intel and AMD (Advanced Micro Devices) corporate web sites (www.intel.com and www.amd.com, respectively), the two primary manufacturers of CPUs. In the generation of this data we omitted CPUs that were designed specifically for server, workstation, or similar applications, because our study focuses on games that are played on personal computers. Additionally, we omitted multi-core CPUs from the data because this new platform represents a significant shift in the technological paradigm of the CPU, whereby processing speed may no longer be the most prevalent indicator of
CPU performance. Similarly, we accessed GPU graphics memory data from the corporate web sites of NVIDIA (www.nvidia.com) and ATI (acquired by AMD on October 2006), the two dominant players in the graphics processor industry. The data on PC game minimum processor speed requirements and minimum graphics memory requirements were, in turn, collected from the web sites of game publishers and game developers, as well as the gaming community Gamespot.com and a major online PC game vendor, Amazon. com. The list of PC games used in our empirical analysis was generated as a result of filtering steps that ensured the reliability of the data. First, we limited the list of PC games to only those that had been reviewed and rated by either one reputable online source, Gamespot.com, or one reputable printed source, PC Gamer magazine (the reputation of these sources was identified by experts from the game development industry). A game which had not been reviewed by either of these sources was discarded on the basis that it did not meet the quality standards of the gaming industry at large, and that its inclusion could therefore reduce the reliability of our data. Second, we limited the list of PC games to those which had been launched in the USA. All in all, we gathered data representing the technological performance levels of these subsystems over a period stretching from August 1995 until the end of 2008. We selected the beginning of the analysed timeframe to correspond with the launch of the Windows 95 operating system that established a new technological platform upon which hardware and PC game software could be developed, thereby producing a significant change in the gaming industry (Hayes and Dinsey 1995). Altogether, 603 CPU, 123 GPU and 3064 PC game related data points were collected and evaluated to reveal the technological evolution curves of the sub-systems and, subsequently, the temporal change in reverse salience as measured by absolute and proportional performance gap.

Results and Discussion

Figures 3 and 4 display the technological performance evolutions that have taken place in two different systemic contexts: the first comprising the CPU and PC game sub-systems, and the second comprising the GPU and PC game sub-systems. In these figures, the produced development curves depict the successively higher levels of technological performance that are delivered by the sub-systems over time. Figures 3 and 4 indicate that the CPU and GPU sub-systems form technological performance frontiers, thereby defining the technological performance potentials for the reverse salient in each technological system context. Further, the figures show that the PC game sub-system trails the technological performance of the CPU as well as the GPU sub-systems over time. These results suggest that the PC game sub-system has the potential to attain higher levels of minimum hardware requirement and increase the level of overall system performance.
Figure 3. CPU and PC game sub-system technological performance evolutions with respect to processor speed.

Figure 4. GPU and PC game sub-system technological performance evolutions with respect to graphics memory.
However, the PC game sub-system does not fully utilise this potential provisioned by the CPU and GPU subsystems. As a result, the gaming performance delivered on the PC system is hampered by the software performance. We therefore ascribe the PC game sub-system as the reverse salient within each systemic context, because it delivers the lowest level of technological performance when compared to the performance of the interdependent hardware sub-system, and at the same time hinders the system level performance delivery. Since the reverse salient limits the level of performance delivered by the technological system, developments in reverse salient performance can indicate overall system evolution. However, to understand system dynamics through the level of performance potential that remains unutilised by the reverse salient, and therefore the system, it is additionally necessary to measure the magnitude of reverse salience. Figures 5 and 6 subsequently plot the absolute performance gap measure of reverse salience and its temporal change, derived from the performance evolutions of the CPU and PC game sub-systems, and the GPU and PC game sub-systems, respectively. Figure 5 highlights two distinct periods: the first denoting absolute performance gap increase (to a value of 2127 MHz) and the second denoting absolute performance decrease, with a turning point in the year 2002. In contrast, Figure 6 illustrates an ever-increasing absolute performance gap between the GPU and PC game sub-systems, particularly emphasizing a rapid incline in the year 2004. This development underlines the PC game sub-system’s growing inability to exploit the graphics memory performance that is available. While these findings denote system level dynamics through the absolute performance gap measure, they are nevertheless impartial to the levels of performance attained by the sub-systems. To compare system development at different points in time, taking into consideration the level of technological evolution across sub-systems, it is necessary to evaluate the proportional performance gap measure of reverse salience. Figures 7 and 8 present the temporal changes in the proportional performance gap measures, derived from the performance evolutions of the CPU and PC game sub-systems, and the GPU and PC game sub-systems, respectively.

![Figure 5.](image-url)
Figure 6. Absolute performance gap measures over time between GPU and PC game sub-systems.

Figure 7. Proportional performance gap measures over time between CPU and PC game sub-systems.

Figure 7 demonstrates two distinct periods of evolution, similar to that observed in the absolute performance gap evolution shown in Figure 5. The initial period signifies an increasing proportional performance gap until the year 2003, followed by a period of proportional performance gap decrease. Interestingly, the latter period coincides in particular with the technical limitations that materialised in the single-core CPU design. Although the introduction of the multi-core CPU2 circumvented the technical reverse salients in the CPU sub-system in 2005, further gains in processor speed performance for the single-core CPU could not be observed after this time (see Figure 3). This is because the transition from the single-core to the multi-core design represents a
shift in the CPU technology paradigm, thereby elevating other performance indicators (e.g. the number of cores) as more central to overall CPU performance than processor speed. The resulting plateau of development in the CPU sub-system has subsequently allowed the PC game sub-system to close the performance gap, both in absolute and proportional terms, through a higher rate of development.

Figure 8. Proportional performance gap measures over time between GPU and PC game sub-systems.

This finding, moreover, suggests that the PC game sub-system may experience a significant shift in time as well. This is because the discontinuous change from single to multi-core CPU design provides the interdependent PC game sub-system with an alternative performance parameter, namely the number of cores, which emerges as being central for software function. In contrast, the proportional performance gap between the GPU and PC game sub-systems shown in Figure 8 oscillates, predominantly between the values of 50% and 75%. This outcome can be attributed to the consecutive levels of graphics performance that increase in a stepwise fashion, specifically in powers of two (e.g. 8–16MB and 16–32 MB), rather than through gradual increments. As a result, the evaluated proportional performance gaps between the technological performance frontier and the reverse salient essentially represent technological generation gaps. Thus, a proportional performance gap of 50% (e.g. when the technological performance frontier is at 16 MB and reverse salient at 8 MB) represents a difference of one generation, while a proportional performance gap of 75% (e.g. when the technological performance frontier is at 32 MB and the reverse salient is at 8 MB) represents a difference of two generations. To further study the dynamics of change in the two system contexts, we analyse the relationship between the absolute and proportional performance gap measures of reverse salience, as represented in Figures 9 and 10. Figure 9 plots the absolute and proportional measures against one another and reaffirms the earlier observed temporal change in reverse salience pertaining to processor speed performance. The figure emphasises a period of reverse salience increase, in both absolute and proportional terms, followed by a period of decrease in both measures, separated by a short, intermediate duration of time. In contrast, the development
of the GPU and PC game sub-systems in Figure 10 shows a highly erratic pattern, leading up to 2004. This sequence of sudden changes is particularly pronounced in the proportional performance gap, and is likely to be caused by successive generation leaps in the PC game sub-system performance, following the leaps in the GPU sub-system performance. Both Figures 9 and 10 illustrate the changes in reverse salience magnitude across time, as well as the intermediate turning points between increasing and decreasing magnitudes.

Figure 9. Plot of absolute and proportional performance gap measures for CPU and PC game sub-systems.
Figure 10. Plot of absolute and proportional performance gap measures for GPU and PC game sub-systems.

Consequently it becomes possible to trace the types of reverse salients that emerge across the timeframe of analysis using the typology of reverse salients depicted in Figure 1. Figures 11 and 12 utilise this typology in identifying reverse salient types with respect to the evolution of the CPU and PC game sub-systems, and the evolution of the GPU and PC game sub-systems, respectively. Figure 11 highlights three periods of development which align with the observations made in Figure 9. The first is a period of alternation between the prohibitive and intermediating reverse salient types, between August 1995 and August 2002 (points A–E in Figure 11). This span of time, overall, coincides with the PC game sub-system falling increasingly behind the technological performance frontier. The second period, between August 2002 and December 2002 (point F in Figure 11), while short-lived, underlines a point of transition in the system dynamics. In turn, during the following period that stretches from December 2002 until December 2008 (points G–K in Figure 11), the PC game sub-system reduces the absolute as well as the proportional performance gap of reverse salience.
Subsequently, the PC game sub-system alternates between the progressive and intermediating reverse salient types during this time. The shift in dynamics indicates that the rate of technological development promoted by firms in the game development industry is increased in relation to the rate of technological development in the CPU industry. This result may additionally point to the greater aptitude of game developing firms to reconcile the level of technology embedded in the
game design and the level of game technology that can be supported by the hardware available in the market. The continuation of performance gap closure, as also evidenced in Figure 7, may suggest that the PC game sub-system is approaching a discontinuous change. A shift from the existing performance parameter of minimum processor speed requirement, to a new central performance parameter, for example the minimum number of processor cores, may therefore materialise in time. This shift in the central performance parameter can simultaneously lead to an abrupt increase in the proportional performance gap and a decrease in absolute performance gap. As a result, the PC game sub-system may shift, in time, from the progressive to the reorienting reverse salient type. Such a shift concurrently denotes the reorientation of the technological focus of game developing firms, who must, in turn, consider the installed base of the hardware technology with respect to the new central performance parameter. Figure 12, conversely, illustrates the oscillating change in reverse salience magnitude also observed in Figure 10. In this manner, the PC game sub-system generally alternates between the progressive and prohibitive reverse salient types over successive periods of time. However, the figure also shows occasions when the reverse salient type can be categorised either as intermediating or prohibitive (points C and H in Figure 12). This finding coincides with the stepwise development that is inherent to graphics related performance (see Figure 8), which increases the probability of observing unchanging proportional performance gap, despite changing absolute performance gap. Overall, however, the sequence of erratic changes indicates the PC game subsystem’s responsive utilisation of available GPU performance, thereby signifying the continuing importance of graphics related technological performance to the game development industry.

Conclusion and Implications

The objective of the paper was to develop measures of reverse salience and a typology of reverse salients that can be applied in the analysis of technological systems. To this end, we have first developed a proportional performance gap measure that quantifies the state of reverse salience and complements the absolute performance gap measure developed earlier by Dedehayir and Mäkinen (2008). This proportional measure importantly allows the comparison of system development at different points in time, taking into account the absolute level of technological evolution across subsystems. Moreover, the absolute and proportional performance gap measures, taken together, inform us of the system level development and at the same time help identify different types of reverse salients. We have, subsequently, demonstrated the applicability of these measures and the typology of reverse salients in an illustrative empirical study of an evolving technological system. Our empirical illustration studied two essential systemic contexts in PC gaming as determined from the PC game manufacturers’ software requirements. We analysed the CPU and PC game sub-systems in the first systemic context and the GPU and PC game sub-systems in the second. In our analyses, we studied the technological evolutions of these sub-systems and evaluated the magnitudes of reverse salience. Our findings showed that reverse salience evolved through periods of increasing followed by decreasing absolute and proportional performance gaps for the CPU and PC game sub-systems. In contrast, with respect to the evolution of the GPU and PC game sub-systems, we observed continuous increase in the absolute performance gap, and oscillation in the proportional performance gap measures. From these results, we determined the types of reverse salients that emerged across time. Our findings from the analysis of the CPU and PC game sub-systems illustrated shifts from prohibitive to intermediating, and from intermediating to progressive reverse salient types. In comparison, the study of the GPU and PC game subsystems demonstrated alternation
between the progressive and prohibitive reverse salient types over consecutive periods of time. In summary, these findings illustrate that the magnitude, direction and types of dynamics in system level evolution can be identified through the reverse salience measures. Overall, our empirical analyses showed that the PC game sub-system delivered the lowest level of performance and therefore hampered the technological system’s delivery of gaming performance. Consequently, the PC game sub-system was determined to be the reverse salient within each systemic context. This finding rests fundamentally on the premise that the reverse salient must be a sub-system which lies within the a priori defined system. However, reverse salients may be caused by factors that are exogenous to the system (Hughes 1983). For example, a reverse salient may emerge when there is excessive resistance from the system’s environment (analogous to enemy forces that oppose a battle line’s forward movement), thereby limiting further performance improvement inside the system. In this manner, external forces may also act as antecedents to the PC game sub-system’s emergence as a reverse salient, given that the development of PC game technology is driven by the strategic actions of firms inside the game development industry and that these actions are contingent on environmental considerations. Such external factors have been demonstrated to influence systemic development in earlier literature; for example, the intervention of institutional agents and policy makers (Araujo and Harrison 2002), changing market behaviour (Adner and Levinthal 2001), as well as network externalities (Katz and Shapiro 1985; Schilling 1998) and the installed base (Katz and Shapiro 1986). Consequently, delimiting the system from its environment emerges as an imperative first step in the analysis of reverse salience. Furthermore, our developed typology of reverse salients allows us to understand the state of system dynamics as well as future trends of system evolution. Hence, a period marked by a progressive reverse salient, may, for example, signify a time of intense competition in the industry to improve central technological performance parameters, resulting in improved benefits to customers and therefore the gaining of market share (e.g. Sheremata 2004). A prohibitive reverse salient, on the other hand, may build-up pressure to remove the development blockage, Q1 where this reverse salient emerges as a significant hindrance. This may, in turn, induce a radical innovation that leads to accelerated technology-based competition in the industry and renders the current prohibitive reverse salient obsolete (Dewar and Dutton 1986). The prohibitive reverse salient may alternatively prove to be inconsequential to overall system performance, in which case this sub-system may be excluded from the system altogether in time, in what could be described as a ‘blitzkrieg’ resolution. Third, the period marked by an intermediating reverse salient is likely to take place in the transition from one reverse salient type to another. Consequently, the intermediating reverse salient may bring about a change in competitive dynamics and, in turn, open up windows of opportunity for strategic manoeuvring (e.g. Lieberman and Montgomery 1988). Conversely, the reorienting reverse salient represents an abrupt change, as the reverse salient sub-system reorients its development focus to a new technological performance frontier. This shift may alter the basis of competition as the performance parameter that is central to the industry is supplanted by another (Christensen 1997). While our developed typology of reverse salients has been illustrated in this paper with limited scope, the method is applicable to larger systemic contexts, as well as to a variety of technological systems. These represent natural extensions of our present work. Our proposed framework focuses on interlinks between different sub-systems and studies the provisioning of technological performance in one sub-system and the utilisation of this performance by another, interdependent sub-system. However, our method does not differentiate between the types of interplay that may exist among sub-systems. A fruitful extension of our present work is therefore to distinguish the
types of system dynamics, such as purely evolutionary or co-evolutionary dynamics, that may result from the different types of sub-system interconnections, such as between simply interlinked and between complementary sub-systems (Teece 1986). Furthermore, while our framework derives the dynamics of change from the respective provisioning and utilisation of technological performance among sub-systems, it does not inform of the length of time required for a particular sub-system to utilise the performance that is made available. Nevertheless, such time-based measurement can reveal the temporal dynamics, in addition to the pure performance based dynamics, in the evolution of technological systems. The development of an additional, time-based measure of reverse salience is subsequently an important avenue for future research. Finally, our proposed typology of reverse salients offers a useful tool for understanding future changes in system dynamics and the competitive landscape (Prahalad and Hamel 1994; Bettis and Hitt 1995). Therefore, by tracing the sequence of reverse salient types over time, subsequent research can, with further empirical studies, increase our understanding of the sequence and nature of shifts between different types of reverse salients. The typology of reverse salients additionally facilitates the recognition and possibly the forecasting of turning points in technological system evolution, as witnessed in the intermediating reverse salient shift with respect to the CPU and PC game sub-system evolutions, and therefore changes in the competitive landscape.

Notes
1. We are grateful for the reviewer’s contribution to this important aspect of system definition.

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