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TRAJECTORIES IN THE EVOLUTION OF TECHNOLOGY:

A MULTI-LEVEL STUDY OF COMPETITION IN FORMULA ONE RACING

Mark Jenkins*
Cranfield School of Management
Cranfield
Bedford
MK43 0AL
United Kingdom
Tel +44 (0) 1234 751122
Fax +44 (0) 1234 750070
m.jenkins@cranfield.ac.uk

Steven Floyd
School of Business Administration
University of Connecticut
2100 Hillside Road
U-41MG
Storrs, CT 06269-1041
Tel (860) 486 3389
Fax (860) 486 6415
steven@sba.uconn.edu

*All correspondence should be addressed to the first author

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TRAJECTORIES IN THE EVOLUTION OF TECHNOLOGY:
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This paper explores the trajectories of three key technologies in Formula One racing at the component, firm and system levels of analysis. The purpose is to understand the evolutionary forces that contribute to the emergence and survival of dominant designs. Based on archival data and contemporaneous accounts of the period from 1967-82, we develop a series of propositions specifying the evolutionary forces acting on technological trajectories within each level of analysis. The resulting framework leads to a set of predictions about relationships between technological transparency, coevolution, and the emergence of dominant designs. Specifically, we argue that when the costs and difficulty associated with transferring component knowledge between firms is low (technological transparency is high), technologies tend to coevolve across firms, leading to the development of complementary technologies and increasing the likelihood of industry dominance. Where transparency is low, however, technologies tend to coevolve across functions within firms, leading to the development of competing technologies across firms and increasing the likelihood of a technology's dominance within the firm. The data and argument suggests that the forces acting on these two types of technological trajectories are self-reinforcing, so that as momentum builds behind a trajectory, it becomes more likely that its evolutionary path will end in either firm- or system-level dominance.

(Technology, Trajectories, Evolution, Competition)

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The centrality of technological innovation to economic development has meant that it provides an enduring basis for research and debate. Work in this area has developed from the economic principles of the production function (Abramovitz, 1956; Solow, 1957) to consideration of managerial processes (Burns and Stalker, 1961), and more recently, to connect innovative processes within the firm to the competitive dynamics within industries. Research has focused on the concept of competitive strategy (Porter, 1983; Abernathy and Clark, 1985), dynamic capability (Teece et al., 1997), institutions (Nelson and Winter, 1977) and coevolution (Levinthal, 1992; Van de Ven and Garud, 1994; Lewin and Volberda, 1999). Studies have considered the relationship between incumbents and new entrants (Christensen and Rosenbloom, 1995), the relationship between innovators and followers (Lieberman and Montgomery, 1988), the distinction between radical and incremental innovation (Banbury and Mitchell, 1995; Dewar and Dutton, 1986) and the implications of competing organizations sharing technologies (Abrahamson and Rosenkopf, 1993; Garud and Kumaraswamy, 1993; Wade, 1995; Cohen et al. 2000).

All of these are important aspects of competitive dynamics and technological innovation. However, they raise questions about: (1) how evolution differs at relevant levels of analysis (technologies, firms, industries) and (2) how coevolutionary forces within or between these levels affect the survival and dominance of technologies. These questions lie at the heart of the relationship between technological innovation, competitive strategy and firm performance. They are challenging, however, because answering them implies complex theory and a rich set of empirical observations. As one approach to this task, we employ an inductive, theory-building method that draws on archival data and contemporaneous accounts. Using Rosenkopf and Nerkar's (1999) definition of analytical levels and Dosi's (1982) notion of technological trajectory as theoretical lenses, we evaluate technology developments over fifteen years of Formula One racing.

Enfolding theory with data leads to a set of propositions on the evolutionary forces acting on technological trajectories within each level of analysis. The resulting framework informs the relationships between technological transparency, coevolution, and the emergence of dominant designs. Specifically, we argue that when the costs and difficulty associated with transferring component knowledge between firms is low (technological transparency is high), technologies tend to coevolve across firms, leading to complementary technologies and increasing the likelihood of industry dominance. When transparency is low, however, technologies tend to coevolve across functions within firms, leading to competing technologies across firms and increasing the likelihood of a technology's dominance within the firm. Moreover, the data and argument suggests that the forces acting on these two technological trajectories are self-reinforcing, so that as momentum builds behind a trajectory, it becomes more likely that its evolutionary path will end in either firm- or system-level dominance. In the discussion, we trace the implications of the model for theories of competition in technologically intensive environments.

Theoretical Background

In prior research, the role of technology in competition has been studied from at least three levels of analysis, focusing on technology itself (Dewar and Dutton, 1986), on firms (Teece et al.,

1997) or on the industry (Abrahamson and Rosenkopf, 1993). Evolutionary theory is concerned with explanation of processes where there are multiple units (individuals, firms, species, etc.) interacting with an environment (Levinthal, 1992). Consistent with this perspective, Rosenkopf and Nekar (1999) propose three levels of analysis within which technological evolution can be observed (Figure 1). First, at the system level, a community of organizations can be defined. Here, interactions between firms lead to the development of industry-wide standards and the co-ordination of products. At this level, the evolution of technology may be influenced by institutional forces (1994) and competitive rivalry (Porter, 1980; 1998). Second, the community of actors within an organization defines the firm level of analysis. At this level, interactions between individuals and sub-units, lead to the integration of technologies to produce products or services (Grant, 1996b). Technological evolution at this level is likely influenced by the boundedly rational decisions of managers (Levinthal and March, 1981) and by the structure and culture of the hierarchy (Conner and Prahalad, 1996). At the third level of analysis, component-specific communities external to the firm can be identified. Within this level, interactions among individuals and groups focus on the development of ideas and lead to the creation of the core knowledge (scientific basis) that forms the foundation of the product (Henderson and Clark, 1990; Tushman and Murmann, 1998).

INSERT FIGURE 1 ABOUT HERE

Rosenkopf and Nerkar (1999) stress the importance of coevolutionary effects both within and across levels of the hierarchy. This concerns the inter-relationships between change at the component, firm and system levels of analysis. Thus, for example, incremental evolution of technology within the firm may be associated with punctuated evolution at the system level (Rosenkopf and Nerkar, 1999). Coevolution may also be observed *within* a given level, as when complementary technologies coevolve within firms or systems, for example. This multiple-level, coevolutionary view highlights historically dependent relationships among the experiences that comprise the development of technology in a competitive context.

The meta-level concept of "technological trajectory" (Dosi, 1982) offers a way to conceptualize the flow of such developments. Trajectories describe the path of a moving object across space and time. Technological trajectories, therefore, may be defined as the series of path dependent experiences that track with the evolution of a technology (Dierickx and Cool, 1989). We propose technological trajectories as the thread connecting one experience to another within and across levels of analysis. Building on Dosi (1982), one can discern three key attributes of such trajectories—their power, momentum and degree of uncertainty.

Power and momentum refer respectively to the degree of influence and impetus behind a trajectory. Among other things, technologies may gain or loose influence and momentum from other technologies, and the relationships between technological trajectories may therefore be described as complementary or competitive (1999). Complementary trajectories increase the power and momentum of another trajectory while competing trajectories reduce them. A high degree of complementarity between two technologies may even lead to their convergence--where progress in one domain fuses directly with progress in another (Levinthal, 1998). The result may be acceleration of the constituent technologies, as illustrated by the momentum given to optics and electronics as the result of their convergence in fibre-optics (Kodama, 1992). In contrast, competing technologies tend to sap one another of power and momentum, because developments in one tend to come at the expense of developments in others. Over time, one trajectory is likely to become dominant, thereby establishing a powerful position, and reducing the power and momentum of alternatives (Abernathy and Clark, 1985). Consistent with this, Dosi (1982) defines the strength of a trajectory by the number of other technologies that it excludes

At the system level, such dominant designs have the effect of stabilizing the technological frontier, as firms accept a particular level of technical and economic performance in order to conform to the industry standard (Rosenkopf and Tushman, 1998). Similarly, dominance of a technology within a firm creates organizational inertia as members or sub-units vested in the technology use their centrality to control information and decision-making (Miller and Friesen, 1980). This effect within firms has also been described as the development of a “paradigm”(Johnson, 1988), a term originally coined to describe the stability of scientific progress at the component level, i.e. within scientific communities (Kuhn, 1962). Thus, dominant technological trajectories produce inertial forces at all three levels of analysis, thereby limiting change to incremental developments that are consistent with the dominant design (Christensen and Bower, 1996).

In addition to power and momentum, uncertainty is the third key attribute of technological trajectories. Early in the life cycle of competing technologies, before much momentum has accumulated behind any one trajectory, there is often no basis for determining which will become dominant (Anderson and Tushman, 1990). Over time, however, the uncertainties surrounding the course of a trajectory are resolved and future developments become increasingly predictable, predictability being perhaps the most desirable feature of dominant designs.

In sum, the multi-level framework offered by Rosenkopf and Nerkar (Rosenkopf and Nerkar, 1999) and the concept of technological trajectory (Dosi, 1982) provide a potentially useful way to describe the evolution of technology in a competitive context. This set of lenses suggests re-framing questions of technological coevolution as questions about the power, momentum and predictability of technological trajectories. More specifically, it suggests the following questions: What are the sources of power and momentum for technological trajectories? How do these differ within levels of analysis? What are the mechanisms of uncertainty resolution of technological trajectories? How do they differ according to level of analysis?

Methodology

Koza and Lewin (1998) outline how longitudinal case studies provide unique opportunities for empirical and theoretical interpretation. Our approach uses a detailed, historical case study to derive new insights about the above questions. The historical case-based perspective involves matching patterns in the data with theoretical explanations (Yin, 1981). Studies that focus on multiple technologies, at multiple levels of analysis, over a significant period of time have the advantage of permitting comparisons between, as well as within, technological trajectories in the search for patterns. Fundamentally, however, even a single historical case may be a fruitful source of explanation when it is accompanied by techniques such as theoretical sampling and enfolding appropriate literature (Eisenhardt, 1989). Some of the best examples of theory development draw on data from only one or a very few cases (Allison, 1971; Burgelman, 1983).

The first and most crucial step in such a design is the selection of the case(s). The principle criterion is the theoretical usefulness of the data for observing relevant phenomena. This “theoretical sampling” approach suggests the need for historical observations from firms competing in a technology-intensive environment. In this instance, we have used longitudinal data of Formula One (F1) racing from 1967-1982 that combines industry, firm and component levels of analysis. In prior work, data from F1 has provided a context for studies that consider the localization of expertise (Pinch and Henry, 1999; Aston and Williams, 1996) and the flow of knowledge between F1 racing and innovation in the motor industry (Foxall et al., 1992).

Today F1 represents the pinnacle of automotive technology. The circuits used in the championship require cars that are both powerful and maneuverable; the industry has been punctuated by several technical revolutions in engine and car design. The pace and competitiveness of the industry is represented by the fact that no team or driver has won the championship consecutively more than four times over fifty years of competition.

In addition to technological intensity the research questions focus on relationships between technical developments and competitive outcomes. There are many factors that may explain competitive success, including industry and corporate effects (McGahan and Porter, 1997; Rumelt, 1991), frequently, this makes it difficult to separate out the influence of technology on competition from these other influences. F1 provides an excellent objective measure of competitive performance - winning races. Whilst there are other success criteria that may be affected by technology (such as sales growth, safety record, TV coverage), race performance (represented by the accumulation of championship points in a given year) is unambiguously accepted within the industry as a key competitive outcome. Moreover, data relevant to technological change is regularly reported in light of its effect on winning. Indeed, the history of the industry is permeated with observations about the relationship between technology and competition. Many of these reports include the observers' "theories-in-use" (Weick, 1995). This mixture_of fact and opinion provides a good context to study the phenomena and develop new theory.

Data for the study draws on a large archival database. The data is uniquely rich because F1 is the subject of constant media attention and generates an enormous amount of written material detailing the actual words and actions of industry players--both individuals as well as firms--all of which has been collected in an industry archive located at the in the southern region of the United Kingdom.[1] Published sources of data include periodicals (*Autosport, Motor Sport, Racecar Engineering*), which provide full race-by-race accounts and detailed descriptions of the "behind the scenes" activity of each team. This data is supplemented other accounts, including autobiographies of the key players to create a detailed chronological database. In order to verify the data, the first author conducted a series of in-depth interviews with the senior managers of the F1 teams included in the study to provide contemporaneous accounts of historical events. A semi-structured scheme was used which asked the individuals to describe critical incidents (Campbell et al., 1970) and account for the performance of the team during the case period. Assertions made by the interviewee were probed using the 'laddering technique', where statements are explored in terms of their saliency to the individual by using the 'why is that important?' question (Eden and Ackermann, 1998). This provides observations from individual actors within all three levels of analysis. Some of the data is commentary, but much is objective,

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[1] BP Library of Motoring at the National Motor Museum. (Beaulieu), United Kingdom.

and in some cases, quantitative in nature. This multi-layered data is necessary and appropriate for inductive research (Eisenhardt, 1989; Yin, 1981).

Study Context

The first Grand Prix was run by the Auto Club de France in 1906, but it wasn’t until 1950 that the first world championship series was held linking the national races held in the UK, Monaco, USA, Switzerland, Belgium, France and Italy. Whilst in many forms of motorsport the race teams buy in the chassis [a term used to describe all aspects of the car except the engine and gearbox], gearbox and engine, the F1 teams design, construct and race their own cars, gearboxes and in some cases their own engines. The term constructor is used to represent this combination of specialized capability. Whereas in the early 1950s automotive manufacturers such as Maserati, Mercedes-Benz and Alfa-Romeo populated F1, by the 1970s it had become the domain of specialist constructors, some of whom also produced high-performance road cars.

This study focuses on a period that begins with the development of the Ford DFV (Double-Four Valve) engine in 1967 and includes the “ground-effect” revolution of the late 1970s that came to an end in 1982. This period has been selected because it includes several technologies, which appear to vary in terms of key factors identified in the analytical framework, i.e. power, momentum and uncertainty.

Case Analysis

The first step in data analysis was to identify technological trajectories. To accomplish this, we divided the data along three historical paths that reflect distinctive technological trajectories: (1)

the events leading up to and including the dominance of the Ford DFV engine from 1967 - 1973, (2) the experience of Ferrari's unique "Flat-12" engine from 1974-1977, and (3) the activity surrounding the revolution in aerodynamics and the emergence of Williams' dominant "ground-effect" design (1978-1982).

The Ford DFV technology involved the use of a purpose-built, 'V8' configuration that enabled F1 constructors to acquire a highly competitive engine at a relatively low price. The significance of the engine was that it formed a structural element of the car and therefore reduced overall weight. The Ferrari "Flat-12" engine technology involved horizontal positioning of the pistons to create a wide, flat engine with a low center of gravity. It represented a radical departure from designs of the period. Ground-effect technology involved the use of the car's underside to create negative lift. The change causes the car to hug the surface of the track and significantly improves cornering speed. Figure 2 illustrates the relative performance levels of these three technologies during the period 1965-1982.

[INSERT FIGURE 2 ABOUT HERE.]

Subsequent inferences in the study are highly sensitive to the definition of technological trajectories. Our choice of the Ford DFV engine, Ferrari Flat-12 and ground-effect trajectories is thus a critical first step in the analysis. In making it, we considered opinions expressed in the archival data and in the interviews with team executives. There was very little disagreement that these three represent key developments during the period, although not everyone agreed about their relative importance. For purposes of expositional clarity, the trajectories are bracketed by distinct sub-periods. Defining them in this way is not meant to suggest their independence, however, and the analysis of the data was seamless in the sense that we did not impose a priori constraints on the time frame for each trajectory. Moreover, given our evolutionary framework, we were especially alert to reports in the data suggesting connections between trajectories. Thus, we recount the case data in three sub-periods and highlight any apparent relationships between developments in one trajectory and those in another.

The Ford DFV Period (1967-1973)

The Ford DFV 'V8'engine was first used competitively in a Lotus 49 at the Dutch Grand Prix in 1967 and caused a sensation by winning its first race. The concept was not just about a better performing engine. Rather, it was about using the engine as part of the car's structure, thus substituting for certain parts of the chassis and creating a lighter and well-powered racecar. The concept of the DFV is illustrated in Figure 3.

[INSERT FIGURE 3 ABOUT HERE.]

The Ford DFV was created by a joint venture between the Ford Motor Company, who funded the project, Cosworth Engineering, who designed and built the engine and Lotus Cars. Lotus designed and built the Lotus 49 around the engine during the 1967 season. The engine became available to other teams in 1968, and quickly became a technological imperative.

"...for ten years that engine pretty well ruled the roost. Anyone with enough money, and in the first year[1968] *it was only £7,500, went to Cosworth and came away with an engine that was capable of winning the next race. That went on for many years which is the reason why there*

are so many British formula one teams, only that reason, only because that engine was available" (Interview with F1 Team Principal)

In 1968 Lotus were joined by McLaren and Matra in using the Ford DFV. The Brabham team followed in 1969. During the early seventies F1 was dominated by the Ford engined 'kit-car'. The term kit-car refers to the fact that the constructor designed and manufactured the chassis and suspension while the engine and gearbox components were supplied from outside. In this case 'the kit' included the Ford DFV engine, manufactured by Cosworth Engineering, and the gearbox built by Hewland Engineering. In 1969 and 1973 a car with a Ford DFV engine won every Grand Prix, the only occasion in the history of F1 that a single engine totally dominated a season. Figure 2 illustrates its performance.

The Ferrari Renaissance 1974-1977

The availability of the Ford DFV meant that the constructors who were vertically integrated and built their own engines and gearboxes, such as Ferrari and BRM, were at a disadvantage. Their 'in-house' capability appeared to be no longer valid. A merger with Fiat in 1969 provided a huge injection of cash and resources for Ferrari, and this allowed the design and construction of a new larger 12 cylinder engine with the cylinders horizontally opposed, creating a powerful, wide engine with a low center of gravity, referred to as a 'Flat-12'. The configuration of the Flat-12 is contrasted with the V8 in Figure 4.

[INSERT FIGURE 4 ABOUT HERE.]

Ferrari had historically seen the engine as the critical aspect of racecar performance: ‘Horsepower was everything to Mr. Ferrari and, following his lead, to most of his engineers. Handling was secondary. Engines to the fore – chassis were regarded merely as brackets to prevent the wheels falling off and to carry the driver and the fuel load.’ (Nye, 1998). The new engine enabled some progress, with a promising performance in 1970, but this was not sustained due to problems with reliability.

However, the huge investment in R&D had included the building of the first purpose-built F1 test track at Fiorano, northern Italy in 1971. In 1973, founder Enzo Ferrari, who had been suffering from ill-health, appointed an understudy to take on the day to day management of the team. Luca di Montezemolo, a 25 year old lawyer, was an unlikely lieutenant to *Il Commendatore*. Many, now see him, however, to have been the catalyst for Ferrari’s most successful period since the 1950s. Montezemolo made some major personnel and managerial changes, including the recruitment of a young driver (Niki Lauda) who worked closely with Mauro Forghieri—the chief designer behind the development of the ‘Flat-12’ engine. This partnership culminated in the 312T car which used the ‘Flat-12’ in combination with Ferrari’s own unique transverse [mounted across the car] gearbox. Ferrari concentrated on an exhaustive development program at Fiorano to ensure that the concept would be reliable as well as fast. The consequence was that, for the first time since 1967, the Ford DFV constructors were seriously challenged.

“Similarly, nobody can claim to have really expected the renaissance of the Ferrari team. It was only the middle of last season that the Italians were staying home from races and having open

disagreements with their star driver. They seemed to be working on the wrong lines both mechanically and managerially. Yet over the winter they have put everything right, revised both machines and management, and were a threat right from the first race in January." Pete Lyons, Autosport, July 4, 1974, p35

The renaissance of Ferrari meant that the teams using the Ford DFV were being challenged by a radically different and unique approach to racecar construction. This produced a number of differing responses. In the case of the Brabham team it seemed that the logical response was to move away from the Ford DFV.

"Halfway through that year [1975] *it was pretty obvious that a twelve cylinder engine – because Ferrari didn't have any other magic at the time; they just powered away on all the quick circuits –was going to end the reign of the* [Ford] *DFV. It was obvious that you had to have more than eight cylinders. And so we started looking around for a twelve."* (Former Technical Director Brabham)

Brabham reached an agreement with Alfa Romeo to supply a 'Flat-12' engine developed by engine specialist Carlo Chiti. This decision had major implications for the team and the design of the car.

"The BT45 [Brabham's first car with the Alfa Romeo engine] *was a completely new car. It was a Flat-12 engine, it was a non-structural engine* [the engine did not form part of the chassis as with the Ford DFV], *so it was a total rethink and I had six months to design and build a Flat-12 Alfa car for the beginning of the '76 season."* (Former Technical Director Brabham)

In contrast, two other constructors - Tyrrell and Lotus - retained the Ford DFV, but developed a more radical chassis in order to increase performance. Tyrrell developed a six-wheeled car with four small wheels at the front designed to improve aerodynamic penetration and to the area of tire gripping surface. The Tyrrell P34 was announced in 1975 and first raced in 1976.

"It was becoming apparent to me that the Ford engine had lost its edge, I mean that it was still producing the same horsepower, but with the success of the Ferrari, the possible success of engines like Matra or anybody else who came along with a Flat-12, V12 or 12 cylinder whatever, you're going to be outclassed apart from that you've got the same [Ford] *engine as many other teams, so you'll be scratching for a little bit here and a bit there and I wanted to make a big breakthrough."* . (Former Technical Director Tyrrell)

Lotus also focused on the aerodynamics of the chassis and in 1977 introduced the first 'ground-effect' car, the Lotus 78, an approach that was enormously successful.

The Ground-Effect Revolution 1978-1982

The original development of aerodynamics in racecars had involved the use of 'wings' or external aerofoils to create downforce which improves grip. In contrast, the ground-effect concept uses the underbody of the car, rather than the upper body or wings, to create a low pressure area, thereby holding the car to the ground and allowing it to travel at far greater speeds when cornering. Two tunnels (or venturi) run along the sides of the car and widen out towards the rear, thereby reducing the pressure and creating a suction effect as the air runs under the car. The principles of ground-effect are summarized in Figure 5.

[INSERT FIGURE 5 ABOUT HERE.]

In 1974 Lotus team owner Colin Chapman asked his Technical Director to take a look at the entire concept of a racecar to see where the performance gains could be made. The Technical Director, along with a specialist aerodynamicist, explored the prospect of producing ground-effect in an F1 car. These two individuals had experimented with these ideas almost ten years earlier when they both worked for BRM. Whilst ground-effect had been developed as a theoretical concept, practical application in F1 was still unresolved. This was achieved by a breakthrough in using 'skirts' - strips down the sides of the car that effectively sealed the area underneath. As with many great discoveries this came almost by accident.
"...until one day the [wind-tunnel] *model was so decrepit we started getting variable results. It would be modified so often, it was made of card and plastic and clay and tape and what have you. We got inconsistent results and we couldn't figure out why and then I noticed that the side pods were sagging and we thought, well what's sagging got to do with it? We thought maybe it's the gap at the edge* [between the car and the ground]*, so we put some card down the edge in a little tiny gap and wumph! We couldn't believe it! We had to re-do* [the test] *four times before we believed it."* Former Lotus Aerodynamicist.

It was the Lotus design that proved to be the most successful innovation, winning the constructors championship in 1978 by a significant margin. Founder Colin Chapman had been responsible for introducing a number of innovations borrowed from aircraft technology such as

the monocoque chassis and had been a prime mover in the Ford DFV project. In contrast to Ferrari's focus on engine horsepower, Lotus had always concentrated on chassis development for technical advancement. In addition Chapman's involvement in the development of the Ford DFV made it unlikely that he would follow Brabham and seek an alternative engine source*:*
"Colin wouldn't consider departing from the Cosworth engine because of the links with Lotus [Cosworth founders Keith Duckworth and Mike Costin had both worked for Lotus in the early sixties]. *He was also very patriotic and would always want a British engine in his cars."*
*(*Former Technical Director of Lotus)

The Lotus 78 established ground-effect technology and many constructors attempted to imitate the design. Here imitation was more practical as the majority was using the same engine configuration as Lotus [Ford DFV] and therefore had only to concentrate on re-design of the chassis. What was particularly significant about ground-effect was that Ferrari's commitment to a Flat-12 engine meant that they were unable to create the narrow under-body profile needed to locate the ground-effect venturi either side of the engine. The narrow Ford V8 was ideally suited to this application, whereas the wide Flat-12 engine meant that there was no space for the venturi. The same problem also applied to Brabham who had shifted to the Alfa Romeo Flat-12 in 1976.
"The basic car was, in the end, quite quick, the engine was good, the aerodynamics were good, and we had a mini recovery, and then we had a slap back right in the middle of that – ground-effect. So now we're stuck with a meter wide Flat-12 engine right where the [ground-effect] *venturi tail wants to start lifting.*" (former technical director, Brabham)

This problem prompted Brabham’s Technical Director to develop the ground-effect in a car with a Flat-12 engine.

We were sitting there racking our brains thinking how else can we have downforce with a Flat-12 engine. The Fan Car bought us time to go back to Alfa and say we need a V12 engine in three months for the beginning of the 78 season. And so we had another complete start again during the 77 season.” (former technical director, Brabham)

The Fan-Car was an attempt to resolve the problem by creating ‘artificial’ ground-effect using a mechanical fan attached to the rear of the car that sucked the air from underneath. The Brabham BT46B ‘fan-car’ was a product of this innovative period and won the Swedish Grand Prix in 1978. Ultimately, it was banned because it was deemed to be outside the regulations and because of the alleged danger to drivers from debris being sucked through the fan.

Whilst Brabham were attempting to find ways to achieve ground-effect with a Flat-12 engine, Ferrari appeared to ignore the phenomena and concentrated on developing their engine and chassis along the same lines as 1974. This however left them hopelessly uncompetitive against the ground-effect cars. *“Maranello’s* [location of Ferrari factory] *Flat-12, still a magnificent racing engine, is incompatible with modern chassis.* [Drivers] *Villeneuve and Scheckter were competing in yesterday’s cars.*” Roebuck (1980). It wasn’t until the appointment of a new Senior Engineer who had previously designed ground-effect cars that the extent of Ferrari’s myopia became clear. “*Everyone else had them* [ground-effect aerodynamics] *for years, but* *until I arrived* [1981] *it was quite firmly believed that they didn't exist."* (Former Senior Engineer, Ferrari)

Following the success of the Lotus 78, Colin Chapman sought to move the concept forward with the more complex Lotus 79 and the Lotus 80. In the Lotus 80, the concept was to increase the ground-effect to the extent that the car needed no external wings, but this proved to be less controllable on the track. In an effort to resolve the problem, Chapman and his design team developed a revolutionary twin chassis car, the Lotus 88. The 88 was, however, the subject of protests by all the major teams, and in 1981, the governing body banned the design.

Williams Grand Prix Engineering (WGPE), formed in 1973, was a relatively new, low budget operation. Designer, Patrick Head, imitated the ground-effect concept developed by Lotus, but in a way that was consistent with stringent financial limitations. It proved to be a simple, but highly effective interpretation of the concept. Whilst the Lotus 80 found the limit of applying the ground-effect concept, the Williams FW07 was considered to be the optimal application of the concept to a Formula 1 car.

"..he [Chapman] *thought that they* [Williams] *had made a better quality job of his original concept. I think he felt that the construction of the cars was probably better than ours."* (Former Chief Mechanic, Lotus)

Following on from the ground-effect revolution a number of constructors had begun to look at alternative materials to use in the construction of the car. Ground-effect worked most effectively when the car was totally rigid; if there were too much flexing of the chassis then this would destabilize the ground-effect. This problem became evident to the technical team at Lotus when they saw a slow motion television shot of one of their cars at the Monaco Grand Prix: *"..the car was coming in to view down the hill in slow motion and as it came round the corner it seemed alive, the whole car was like a snake, we realized that it just shouldn't be doing that, that's not a stable platform to work the car from."* (Former Technical Director of Lotus)

A change of chassis construction from aluminum to carbon fiber solved the problem. Brabham were the first team to use carbon fiber as part of their chassis, but it was McLaren in 1980 who came up with the first full carbon composite monocoque. Using specialist composite fabricator Hercules the McLaren team were the first team to involve a specialist to build their entire monocoque. "*the next day we got on a plane with the drawings, with the model in the overhead locker, and off we went to Salt Lake City and that was it – just like that it developed to Hercules building the first monocoque for us." (*Former Technical Director, McLaren).

We have attempted to distill some of the key aspects of the development of this industry during the period 1967-1982. Table 1 summarizes these as they relate to each of three levels of analysis outlined in Figure 1.

INSERT TABLE 1 ABOUT HERE

Competitive Dynamics of Technological Trajectories

Table 2 reviews the description of technological trajectories that our case analysis suggests. Rows identify the level of analysis, and columns show the attributes or dimensions of technological trajectories suggested by the analytical framework. The three levels of analysis are “nested” within one another, such that systems are comprised of multiple firms and firms are comprised of multiple component technologies. Columns represent a logic where trajectories in physical objects start as the result of an application of physical force. We have labelled such force “power,” because in a technological trajectory, velocity appears to depend on the degree of influence wielded by the technology, i.e. the extent to which it affects the behaviour of actors within the communities at each level of analysis. (Interestingly, this relationship does not appear to be a linear one, as will be discussed below.) Following the logic of the metaphor, momentum accelerates the velocity of a trajectory, and this, too, appears to differ according to the nature of influence within level of analysis. Finally, like physical trajectories, actors within each community attempt to influence the direction of technological development. Hence, the third column suggests the decision-making or uncertainty resolution mechanisms employed at each level.

INSERT TABLE 2 ABOUT HERE

Sources of Power, Momentum and Uncertainty Resolution

All knowledge begins within individuals (Grant, 1996b; Nonaka, 1994; Spender, 1996), we therefore begin the description of trajectories at the component level, the world of ideas, where the community’s key concern is the development of knowledge. Actors at this level of analysis include, for example, the design team within Cosworth who developed the Ford DFV, Mauro Forghieri and the design group within Ferrari who produced the Flat-12 engine and the Technical Director and aerodynamicist at Lotus who developed the ground-effect concept. At these early stages, trajectories are relatively uncontaminated by other forms of knowledge or interests. As the aerodynamicist at Lotus suggested, the source of an idea’s power at this point is its ability to demonstrate “a better way of doing things.” As a concept “proves” itself along these lines, it gains increasing attention and influence within the community. Proof of concept, however, relies on methods and approaches that are grounded in a particular belief system. A trajectory’s ability to get started, therefore, may be restrained by its lack of fit with the dominant paradigm (Kuhn, 1962). Thus, for example, it took nearly a decade for an idea from aerodynamics to be accepted in racecar design. But in Ferrari, the development of the Flat-12 engine was launched directly from the organization’s collective belief in engines. In each case, the strength of an idea lies in its ability to solve a particular problem, thereby ruling out alternatives (Dosi, 1982) and focusing activity around a given technical direction.

> **Proposition 1: Technological trajectories start at the component level as the result of this community’s belief in the problem-solving potential of a new idea.**

At the firm level, a trajectory appears to gain influence by creating inter-dependencies with component technologies already in place. Adoption of the Ford DFV engine, for example, required radical changes in chassis design to take advantage of its structural features. In Ferrari, “horsepower was everything” (Nye, 1998), and thus everything was built around the engine, including the chassis design and gearbox. Indeed, the power of Ferrari’s commitment to engines, undermined consideration of the ground-effect concept, while Lotus’ focus on the chassis provided an ideal environment for the idea to take hold. These and the relative power of one component over others, therefore, seem to be based on the number and strength of inter-dependencies it creates with other technologies. The concept of inter-dependencies as a source of power within the firm is consistent with knowledge-based theories of the firm wherein hierarchies are seen principally as mechanisms for integrating and applying the knowledge of technical specialists (Conner and Prahalad, 1996; Grant, 1996a). In addition, the number and strength of inter-dependencies has been shown to be a source of influence in studies of intra-organizational power (Hinings et al., 1974).

> **Proposition 2: Technological trajectories take hold and gain power within firms by virtue of the number and strength of inter-dependencies they create with other component technologies.**

At the system level, the power of a trajectory appears to be related to the level of consensus among firms, and in particular, the degree to which firms agree about the value of a technology to their (individual) success. For example, the Ford DFV engine emerged as the agreed upon design for Lotus, McLaren, Matra and Brabham in less than two years. Similarly, the influence of ground-effect was represented by rapid widespread adoption within the system. Both these technologies became dominant designs at the system level. Ferrari's Flat-12 design, in contrast, gained very little power at the system level with only one other team (Brabham) moving in a similar direction. The difference appears to be the extent that the technologies were perceived as a viable means of improving performance. Importantly, however, these perceptions about what creates success were bounded by higher order norms within the system, so that, for example, trajectories that are outside regulatory norms (like the Brabham fan car) develop very little power at the system level. This explanation resonates with an institutional theorists' explanation of technological evolution wherein adoption is driven by collective belief, social norms and formal regulations (Scott, 1995).

> **Proposition 3: The power of a technological trajectory at the system level is rooted in the degree of consensus among key actors within firms about the**

> **technology's role in performance, which is influenced and constrained by social norms and regulations.**

Momentum develops as the result of additional or reinforcing applications of power. Thus, the theoretical arguments for power contain within them an explanation for how momentum develops at each level (Table 1). At the component level, momentum is gained by technical achievement. This may be defined within the paradigm then operating or, in rare cases, by a revolutionary approach (Kuhn, 1962). At the firm level, actors are concerned with more than technical achievement, however, and a trajectory's momentum at this level is accelerated by a belief within the firm that it can achieve a broader range of goals. Thus, critical inter-dependencies may be created by a technology when it is seen to contribute to survival (Aldrich, 1979), stakeholder satisfaction (Pfeffer and Salancik, 1978), economic profit and other performance-related goals. At the system level, momentum-building processes are similarly grounded in the perceptions of actors, here the consensus about a technology emerges as a legitimation process, wherein links to performance are defined on the basis of observed successes as constrained by formal and informal norms of the community (Scott, 1995).

> **Proposition 4: The momentum of technological trajectories is accelerated by perceptions among actors at the component level that the solution contributes to technical achievement, at the firm-level that it contributes to goal achievement and at the system level that it contributes to social legitimacy.**

Thus, the momentum created behind the Ford DFV engine at the system level developed as the belief spread that anyone with enough money could go to Cosworth and come away with an engine that was capable of winning races. Ferrari's investments in the Flat-12 engine accelerated as it was seen to be the key to the team's renaissance—not only in technical performance but in rebuilding the team's status and prestige among key stakeholders (owners, sponsors, publics). Finally, although the ground-effect concept was initially impeded at the component level because it did not fit the paradigm, once the dramatic improvements it made in performance were understood, it spurred a revolution in chassis design within the technical community.

The description of technological trajectories would not be complete without identifying the means that actors use to resolve uncertainties about the trajectory's path. Resolution of such uncertainties becomes important as actors individually or collectively attempt to anticipate the future course of events and shape them in ways that contribute to their perceived self-interest. These efforts imply a desire to understand and influence the direction and/or velocity of the technology's development. Thus, uncertainty-reducing and decision-making processes within each level can be described in accordance with the explanations of power and momentum. Consistent with the institutional explanations of consensus at the system level, political processes, including negotiation, bargaining and compromise are the chief means by which actors settle differences and come to a consensus about the role of a particular technology (Scott, 1995). At the firm-level, technological uncertainties are reduced as boundedly rational actors attempt to make judgments about the means to achieve organizational goals (Simon, 1957). Finally, at the component level, where science and engineering concerns dominate, the principal of uncertainty reduction is learning, most often in the form of experimentation.

> **Proposition 5A: Experimental learning processes are used to reduce uncertainty and make decisions related to technological trajectories at the component level.**
> **Proposition 5B: Boundedly rational decision making processes are the source of uncertainty reduction at the firm level.**

> **Proposition 5C: Political processes in the form of bargaining, negotiation and compromise govern decision-making and uncertainty-reduction at the system level.**

Thus, for example, at the component level, the development of ground-effect technology followed a path of numerous experiments by designers within Lotus, Brabham, Williams and others. Learning occurred at the component level as one iteration won out over the rest, and ultimately, Williams' formula proved optimal. The evolution of ground-effect technology was also shaped by decisions to adopt it at the firm level. In each case, these decisions are based not only on actors' attempts to improve performance, but also, on the resource and other constraints imposed by unique firm goals. Thus, Ferrari and Brabham attempted to adapt the technology to suit larger engines, while Williams adapted it to fit their financial constraints. Finally, the political processes at the system level—that occurred within the regulatory body (Fédération Internationale de l'Automobile -FIA) and among its members (the constructors)—led to agreements about how ground-effect should be constrained, including the ban on the use of "artificial" means, i.e. Brabham's Fan-Car.

In sum, technological trajectories are social phenomena, created and sustained by belief within the relevant communities of action. Sociological processes within each community affect their growth, velocity and direction. Good explanations for their development therefore include the sociology of science (Kuhn, 1962), bounded rationality (Simon, 1957) and institutional mechanisms (Scott, 1995). This description offers a synthesis of the evolutionary forces affecting technology trajectories at different levels of analysis. By itself, however, it does not add to what we know about how a technology evolves into a position of dominance. Indeed, institutional and competitive influences on this process have been described in prior research (Abrahamson and

Rosenkopf, 1993). Nor does the framework address questions about the coevolution of technology. In the next section, however, we suggest an explanation of dominance that, while consistent with prior theory, moves beyond earlier models--tracing the roots of dominance to the nature and coevolution of component technologies. To do so requires animating our discussion by tracing a trajectory's path within and between the levels of analysis.

Tracing the Paths of Technological Trajectories

Power explains the impetus and velocity of technological trajectories, but what governs their direction? Figure 6 suggests that the relative transparency of component knowledge plays a key role in determining the coevolutionary forces that direct a technology's development. The nature of these coevolutionary forces (primarily within or between firms), then, explains whether a technology's path is more likely to end in firm- or system-level dominance.

INSERT FIGURE 6 ABOUT HERE

Consistent with prior theory (Kogut and Zander, 1992), we define transparency as the cost and difficulty involved in transferring technology among individuals. Distinct from inimitability (Barney, 1991), which describes a similar phenomenon between firms, we reserve the concept of transparency to the component level. It is therefore associated with codifiability (Boisot, 1998; Winter, 1987) and the extent to which component knowledge can be easily shared among technical specialists (Wade, 1995).

As the figure shows, when component technology is transparent, critical knowledge elements are easily shared among technical professionals within firms. Under conditions of competitive rivalry and demand for new products, knowledge diffusion leads to multiple applications of the technology within firms. The technology changes as it is adapted to idiosyncratic firm goals and as it is fused with other path dependent processes (Cohen and Levinthal, 1990; Nelson and Winter, 1977; Rosenkopf and Nerkar, 1999). These variations coevolve across rival firms as some applications compete more successfully than others.

In addition, firm-level processes that serve to bundle the component technology in different ways stimulate additional variety in the form of complementary technologies. Some of these arise from other functions or divisions within the firm. As the technology is adopted widely at the system level, still other complementary technologies develop through relationships with outside organizations (e.g. suppliers). Thus, a high level of transparency tends to push technology development in the direction of coevolution across firms (inter-firm coevolution). Transparency stimulates variety between firms, as well as within them. This coevolutionary process may lead to dominance of the technology at the industry level.

The Ford DFV engine offers the best example of transparent component technology in the Formula One data. Ford and Cosworth provided detailed engineering drawings and technical assistance to virtually any team that was willing and able to pay for them. However, there was still a great deal of variation among firms in terms of how the technology was applied. The coevolution of these alternative interpretations produced an increasingly refined approach supported by the development of many complementary technologies—both of which further reinforced adoption within the industry. In the end, the technology was judged within most firms to be “the only way to compete,” i.e. it was the dominant industry design.

When transparency is low, diffusion of ideas within the technical community proceeds more slowly. Sometimes real interest is limited to only one or a few individuals or groups. Often these people are concentrated in a particular firm, whose goals and history happen to align with the technology, and sometimes, the firm’s goals and/or culture create the technology. Whether in one or a few firms, then, the technology tends to take hold. Coevolutionary processes are primarily based in the interactions between the new technology and existing component technologies within individual firms. Once technologies become integrated across functions and embedded in the organizational routine, coevolutionary forces within particular firms tend to decrease transparency even further because the knowledge associated with the technology becomes more tacit (Nelson and Winter, 1977; Nonaka, 1994).

This inimitability may be good for competitive advantage (Barney, 1991), but it limits inter-firm coevolution and the development of complementary technologies. Trajectories that go down this path, then, are not likely to reach dominance at the system level. Where the technology is particularly critical to firm goals, however, it might be said that such technologies may lead to firm-level dominance. This dominance is significant because it leads to sub-unit power and functional orientation which, in turn, may influence firm goals and the assimilation/creation of new technologies.

Ferrari's Flat-12 engine was clearly not transparent to designers in other firms. In some respects this was a result of the fact that the technology originated within Ferrari. Indeed, it is likely that the level of transparency in a component technology varies depending on its origin. (Note the feedback loops in Figure 6). If it comes from an established technical discipline, such as aerodynamics, it is more likely to be highly codified and thus transparent. If it comes from a relatively small group of engineers within a single firm where there is less need to be explicit, however, the technology is less likely to be codified. The Flat-12 originated within the Ferrari culture, and lack of transparency limited coevolution between firms. Complementary technologies were impeded, and although it became dominant within the firm, the Flat-12 never became dominant at the system level, despite the efforts of Brabham to adopt the technology.

Thus,

> **Proposition 6: The transparency of new component technologies affects the direction of their development: higher levels increasing interactions between firms and lower levels increasing coevolutionary processes across functions or divisions within firms.**
>
> **Proposition 7: Technological coevolution *between* firms *increases* the number and variety of complementary technologies while technological coevolution *within* firms *limits* the number and variety of complementary technologies.**
>
> **Proposition 8: Highly transparent component technologies are more likely to become dominant at the system level.**

Conclusion

In summary we develop two central themes concerning the nature of technological innovation and the evolution of dominant designs. The first is the differences in terms of power, momentum and uncertainty reduction in trajectories at differing levels of analysis. Clarifying such differences helps us to disaggregate some of the complexity and interdependencies within the innovative process. As a consequence, we are able to present a series of fine-grained propositions concerning the nature of technological evolution. The second is the concept of technological transparency and its role in either generating the complementary technologies necessary for systems level acceptance (dominant design) or building firm level dominance and competitive advantage amongst competing organizations.

The concept of technological transparency also underlines the contrasts between the development of intra-firm proprietary technologies and inter-firm technologies that coevolve at the industry level. The tension between these underlines the importance of a dynamic, multi-level model. Each level of analysis provides a distinctive source of momentum. Firms' seek to achieve their particular goals and develop technologies that provide advantage through superior individual technologies and the synergies created by inter-dependencies across technologies. Component level-communities seek to ensure the dominance of a particular technological solution and the achievement of technological outcomes. In contrast, the system seeks balance and legitimacy in how the technology performs--along political, economic and social dimensions.

The strength and direction of a trajectory evolves across levels of analysis. Trajectories take shape first at the component level (technological trajectory) and may develop later at the systems level (socio-technological trajectory). At the firm level, they are influenced by an architecture of inter-dependent technologies (Henderson and Clark, 1990). The tensions and contrasts between levels--the need to reconcile technological imperatives with firm level goals and systems level acceptance—create momentum and drive the trajectory's development.

Table 1: Summary of Key Aspects of Case Outline

	Ford DFV Period 1967-1973	Ferrari Renaissance 1974-1977	Ground-effect Revolution 1978-1982
System-level community	Ford DFV becomes the basis of dominant design; with complementary designs in gearbox and chassis	Period of ferment and variation between Ford DFV and Ferrari Flat-12	Ground-effect becomes accepted standard, including use of 'skirts'
Firm-level community	Alliance between Lotus and Cosworth create Ford DFV but technology is easily acquired by competing firms	Firms either innovate (6 wheel Tyrrell; ground-effect Lotus) or imitate – Brabham with Alfa Romeo engine	Lotus develop innovation but others follow and imitate concepts
Component-level community	Development of engine and related components	Distinction between engine driven innovation; and chassis driven innovation	Development of ground-effect aerodynamics and related materials (carbon composite); concept of Flat-12 engine undermined by need for underbody venturi

Table 2:
Sources of power, momentum and uncertainty resolution within technological trajectories at the system-, firm- and component-levels of analysis

	Sources of Power	**Sources of Momentum**	**Uncertainty Resolution Process**
System-level community	Consensus	Legitimacy (Dominant Design)	Politics
Firm-level community	Technical Inter-dependencies	Goal achievement	Bounded rationality
Component-level community	Development of the technological paradigm	Technical achievement	Experimentation

Figure 1: Levels of Analysis of Technological Evolution (Rosenkopf and Nerkar, A. 1999)

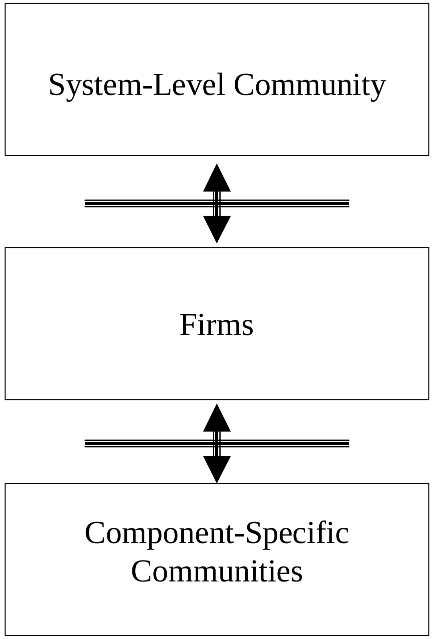
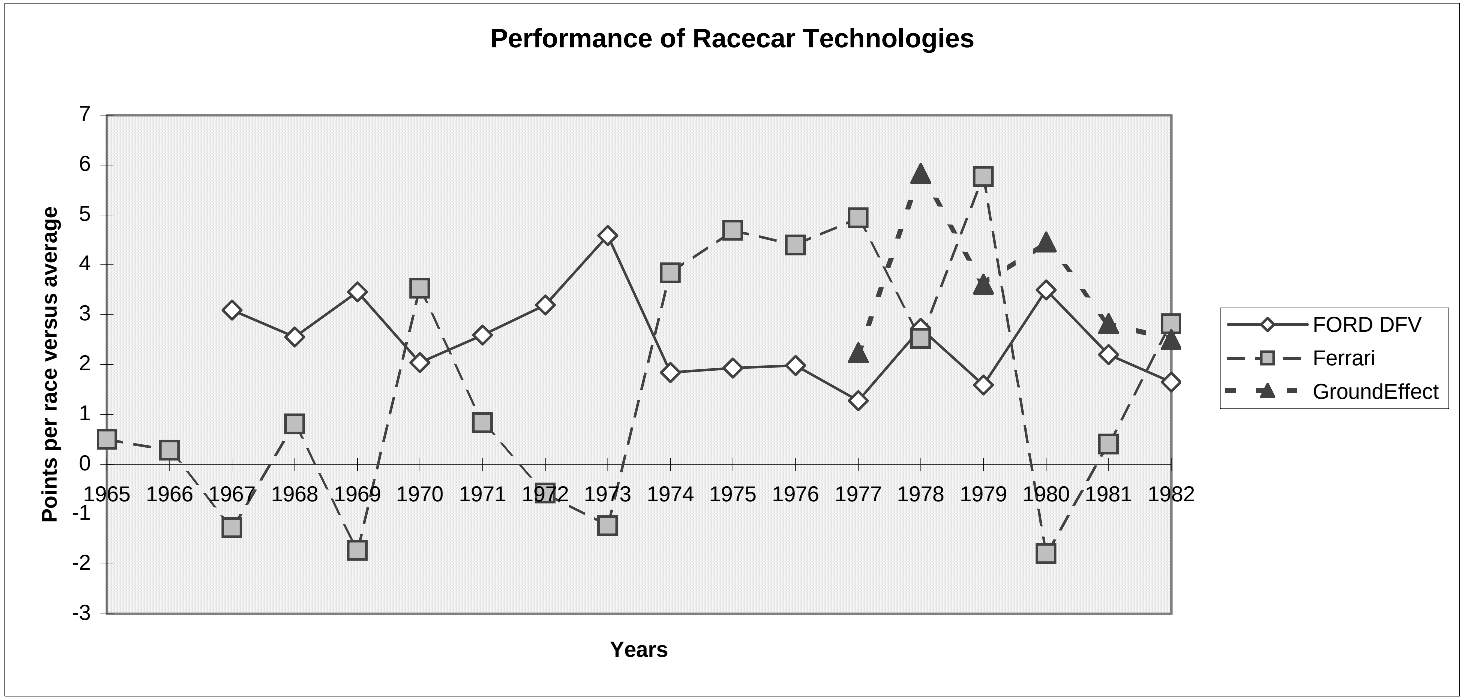
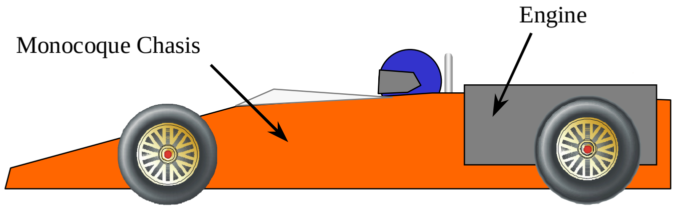


Figure 2: Relative Performance of Racecar Technologies

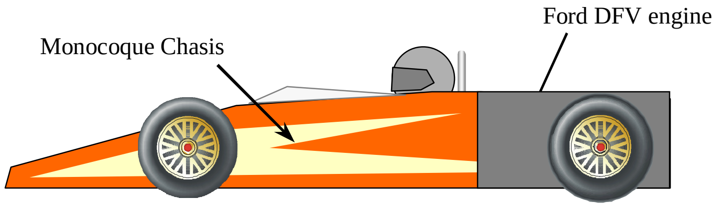


Note: The vertical axis represents the relative race performance of a particular technology based on championship points accumulated during the year. Each car is awarded 10 points for a win, six points for second, four points for third and from three to one point from fourth to sixth respectively.

Figure 3: Principles of the Ford DFV

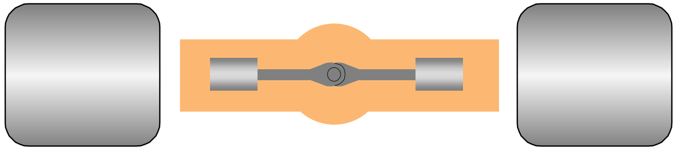


Racecar configuration Pre 1967

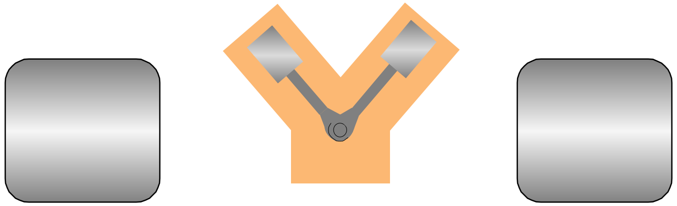


Lotus 49 configuration 1967

Figure 4: Flat-12 and V8 engine configuration

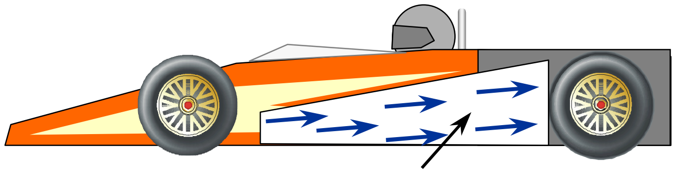


Ferrari ‘Flat 12’ engine
(from rear of car)

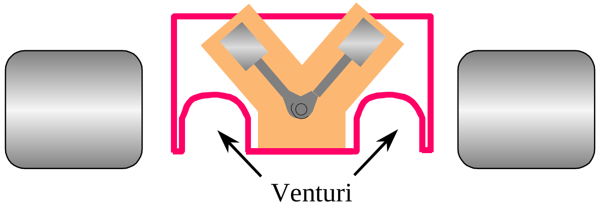


Ford DFV ‘V8’ Engine
(from rear of car)

Figure 5: Ground-effect Racecar

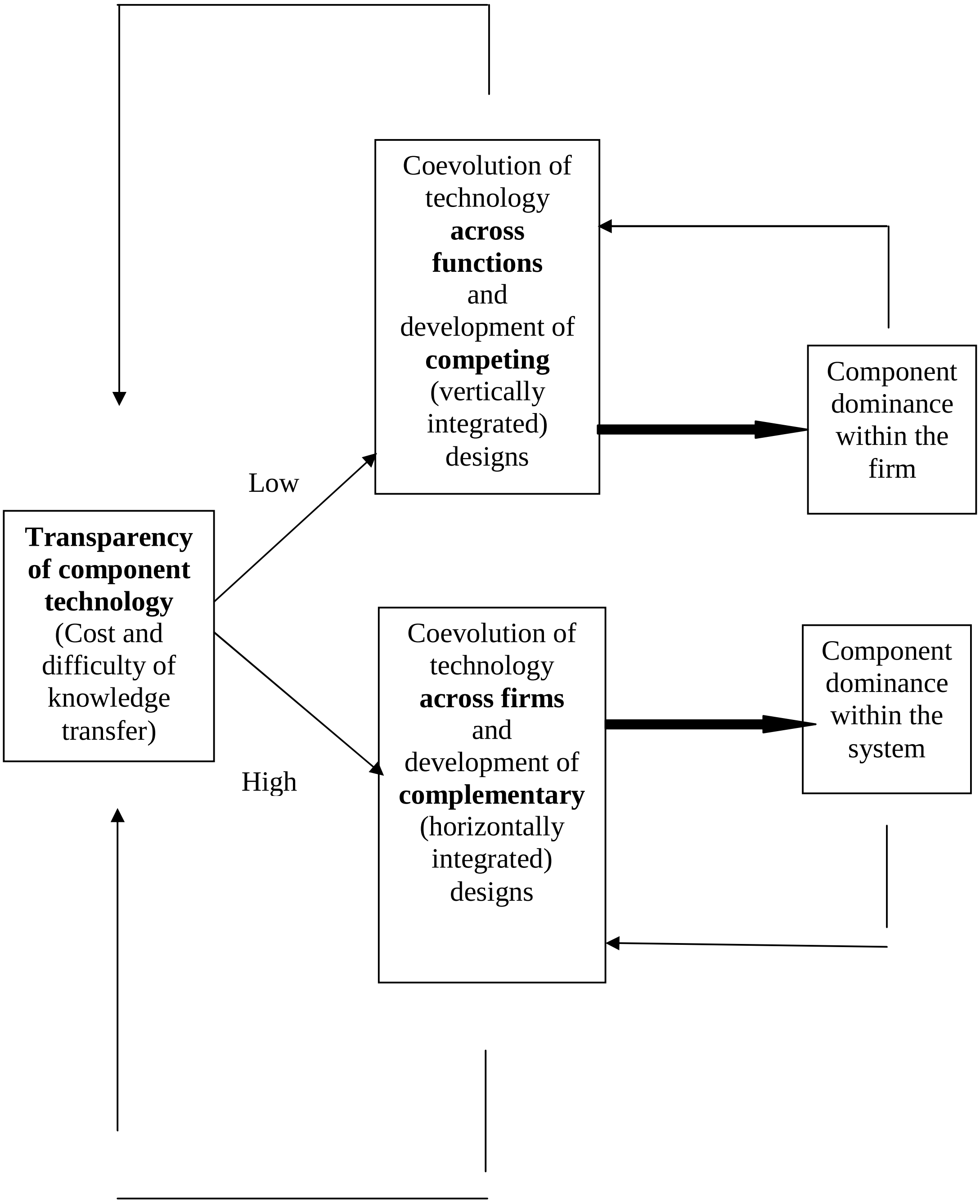


Venturi from side of car



Location of ground effect venturi in car fitted with Ford DFV
(from rear of car)

Figure 6: Technological Transparency and the Coevolution of Innovations



References

Abernathy, W.J. and Clark, K.B. (1985) Innovation: Mapping the winds of creative destruction. *Research Policy* **14**, 3-22.

Abrahamson, E. and Rosenkopf, L. (1993) Institutional and Competitive Bandwagons: Using Mathematical Modelling as a Tool to Explore Innovation Diffusion. *Academy of Management Review* **18**, 487-517.

Abramovitz, M. (1956) Resource and Output Trends in the United States since 1870. *American Economic Review* **46**, 4-23.

Aldrich, H.E. (1979) *Organizations and Environments*, Englewood Cliffs, NJ: Prentice-Hall.

Allison, G.T. (1971) *The Essence of Decision - Explaining the Cuban Missile Crisis*, Boston: Little Brown and Company.

Anderson, P. and Tushman, M. (1990) Technological Discontinuities and Dominant Designs: A Cyclical Model of Technological Change. *Administrative Science Quarterly* **35**, 604-633.

Aston, B. and Williams, M. (1996) *Playing to Win: The Success of UK Motorsport Engineering*, London: Institute of Public Policy Research.

Banbury, C.M. and Mitchell, W. (1995) The Effect of Introducing Important Incremental Innovations on Market Share and Business Survival. *Strategic Management Journal* **16**, 161-182.

Barney, J.B. (1991) Firm resources and sustained competitive advantage. *Journal of Management* **17**, 99-120.

Boisot, M.H. (1998) *Knowledge Assets: Securing Competitive Assets in the Information Economy*, Oxford: Oxford University Press.

Burgelman, R.A. (1983) A Process Model of Internal Corporate Venturing in the Diversified Firm. *Administrative Science Quarterly* **28**, 233-244.

Burns, T. and Stalker, G. (1961) *The Management of Innovation*, London: Tavistock Publications.

Campbell, J., Dunnette, M., Lawler, E. and Weick, K. (1970) *Managerial Behaviour, Performance and Effectiveness*, New York: McGraw-Hill.

Christensen, C.M. and Bower, J.L. (1996) Customer Power, Strategic Investment, and the Failure of Leading Firms. *Strategic Management Journal* **17**, 197-218.

Christensen, C.M. and Rosenbloom, R.S. (1995) Explaining the attacher's advantage: technological paradigms, organizational dynamics, and the value network. *Research Policy* **24**, 233-257.

Cohen, W.M. and Levinthal, D.A. (1990) Absorptive Capacity: A New Perspective on Learning and Innovation. *Administrative Science Quarterly* **35**, 128-152.

Cohen, W.M., Nelson, R.R. and Walsh, J.P. (2000) Protecting Their Intellectual Assets: Appropriability Conditions and Why U.S. Manufacturing Firms Patent (or Not). Anonymous

Conner, K.R. and Prahalad, C.K. (1996) A Resource-based Theory of the Firm: Knowledge Versus Opportunism. *Organization Science* **7**, 477-501.

Dewar, R.D. and Dutton, J.E. (1986) The Adoption of Radical and Incremental Innovations: An Empirical Analysis. *Management Science* **32**, 1422-1433.

Dierickx, I. and Cool, K. (1989) Asset Stock Accumulation and Sustainability of Competitive Advantage. *Management Science* **35**, 1504-1511.

Dosi, G. (1982) Technological paradigms and technological trajectories. *Research Policy* **11** 147-162.

Eden, C. and Ackermann, F. (1998) *Making Strategy: The Journey of Strategic Management*, London: Sage Publications.

Eisenhardt, K.M. (1989) Building Theories from Case Study Research. *Academy of Management Review* **14**, 532-550.

Foxall, G.R., Fawn, J.R. and Johnston, B.R. (1992) Innovation in Grand Prix Motor Racing. II. Extension of the Population Ecology Model. *Technovation* **12**, 1-14.

Garud, R. and Kumaraswamy, A. (1993) Changing Competitive Dynamics in Network Industries: An Exploration of Sun Microsystem's Open Systems Strategy. *Strategic Management Journal* **14**, 351-369.

Grant, R.M. (1996a) Prospering in dynamically competitive environments: organizational capability as knowledge integration. *Organization Science* **7**, 375-387.

Grant, R.M. (1996b) Toward a Knowledge-based Theory of the Firm. *Strategic Management Journal* **17**, 109-122.

Henderson, R.M. and Clark, K.B. (1990) Architectural Innovation: The Reconfiguration of Exisitng Product Technologies and the Failure of Established Firms. *Administrative Science Quarterly* **35**, 9-30.

Hinings, C.R., Hickson, D.J., Pennings, J.M. and Schneck, R.E. (1974) Structural Conditions of Intraorganizational Power. *Administrative Science Quarterly* **19**, 22-44.

Johnson, G. (1988) Rethinking Incrementalism. *Strategic Management Journal* **9**, 75-91.

Kodama, F. (1992) Technology Fusion and the New R&D. *Harvard Business Review* **70**, 70-78.

Kogut, B. and Zander, U. (1992) Knowledge of the firm, combinative capabilities, and the replication of technology. *Organization Science* **3**, 383-397.

Koza, M.P. and Lewin, A.Y. (1998) The Co-evolution of Strategic Alliances. *Organization Science* **9**, 255-264.

Kuhn, T. (1962) *The Structure of Scientific Revolutions*, edn. Chicago, IL: Chicago University Press.

Levinthal, D.A. (1992) Surviving Schumpeterian Environments: An Evolutionary Perspective. *Industrial and Corporate Change* **1**, 427-443.

Levinthal, D.A. (1998) The Slow Pace of Rapid Technological Change: Gradualism and Punctuation in Technological Change. *Industrial and Corporate Change* **7**, 217-247.

Levinthal, D.A. and March, J.G. (1981) A Model of Adaptive Organizational Search. *Journal of Economic Behavior and Organization* **2**, 307-333.

Lewin, A.Y. and Volberda, H.W. (1999) Prolegomena on Coevolution: A Framework for Research on Strategy and New Organizational Forms. *Organization Science* **10**, 519-534.

Lieberman, M.B. and Montgomery, D.B. (1988) First-Mover Advantages. *Strategic Management Journal* **9**, 41-58.

McGahan, A.M. and Porter, M.E. (1997) How Much Does Industry Really Matter? *Strategic Management Journal* **18**, 15-30.

Miller, D. and Friesen, P.H. (1980) Momentum and revolution in organizational adaptation. *Academy of Management Journal* **23**, 591-614.

Nelson, R.R. and Winter, S.G. (1977) In search of useful theory of innovation. *Research Policy* **6**, 36-76.

Nonaka, I. (1994) A Dynamic Theory of Organizational Knowledge Creation. *Organization Science* **5**, 14-37.

Nye, Doug. An Appreciation of Enzo Ferrari (Part B0. 98.

Pfeffer, J. and Salancik, G.R. (1978) *The External Control of Organizations: A Resource Dependence Perspective*, New York: Harper and Row.

Pinch, S. and Henry, N. (1999) Discursive aspects of technological innovation: the case of the British motor-sport industry. *Environment and Planning* **31**, 665-682.

Porter, M.E. (1980) *Competitive Strategy: Techniques for Analyzing Industries and Competitors*, edn. New York: The Free Press.

Porter, M.E. (1983) The Technological Dimension of Competitive Strategy. In: Rosenbloom, R.S., (Ed.) *Research on Technological Innovation, Management and Policy*, Greenwich, CT: JAI Press

Rosenkopf, L. and Nerkar, A. (1999) On the Complexity of Technological Evolution: Exploring Coevolution Within and Across Hierarchical Levels in Optical Disc Technology. In: Baum, J.A.C. and McKelvey, W., (Eds.) *Variations in Organization Science: In Honor of Donald T. Campbell*, pp. 169-183. Thousand Oaks, CA: Sage Publications

Rosenkopf, L. and Tushman, M.L. (1994) The Coevolution of Technology and Organization. In: Baum, J.A.C. and Singh, J.V., (Eds.) *Evolutionary Dynamics of Organizations*, pp. 403-424. New York: Oxford University Press

Rosenkopf, L. and Tushman, M.L. (1998) The Coevolution of Community Networks and Technology: Lessons from the Flight Simulation Industry. *Industrial and Corporate Change* **7**, 311-346.

Rumelt, R.P. (1991) How Much Does Industry Matter? *Strategic Management Journal* **12**, 167-185.

Scott, W.R. (1995) *Institutions and Organizations,* Thousand Oaks, CA: Sage Publications.

Simon, H.A. (1957) *The New Science of Management Decision*, New York: Harper.

Solow, R. (1957) Technical Change and the Aggregate Production Function. *Review of Economics and Statistics* **39**, 312-330.

Spender, J.-C. (1996) Making Knowledge the Basis of a Dynamic Theory of the Firm. *Strategic Management Journal* **17**, 45-62.

Teece, D.J., Pisano, G. and Shuen, A. (1997) Dynamic Capabilities and Strategic Management. *Strategic Management Journal* **18**, 509-533.

Tushman, M.L. and Murmann, J.P. (1998) Dominant Designs, Technology Cycles, and Organizational Outcomes. In: Anonymous *Research in Organizational Behavior*, pp. 231-266. Greenwich, CT: JAI Press Inc.

Van de Ven, A. and Garud, R. (1994) The Coevolution of Technical and Institutional Events in the Development of an Innovation. In: Baum, J.A.C. and Singh, J.V., (Eds.) *Evolutionary Dynamics of Organizations*, pp. 425-443. New York: Oxford University Press

Wade, J. (1995) Dynamics of Organisational Communities and Technological Bandwagons: An Empirical Investigation of Community Evolution in the Microprocessor Market. *Strategic Management Journal* **16**, 111-133.

Weick, K.E. (1995) *Sensemaking in Organizations*, Thousand Oaks, CA: Sage Publications.

Winter, S.G. (1987) Knowledge and competence as strategic assets. In: D. Teece, (Ed.) *The Competitive Challenge - Strategies for Industrial Innovation and Renewal*, pp. 159-184. Cambridge, MA: Ballinger

Yin, R.K. (1981) The Case Study Crisis: Some Answers. *Administrative Science Quarterly* **26**, 58-65.