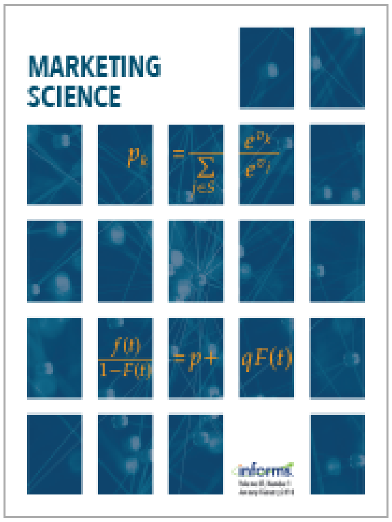

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Findings

Innovations' Origins: When, By Whom, and How Are Radical Innovations Developed?

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Innovation research tends to consider only the post-commercialization period or examine a few innovations through case studies. In this study, we examine 29 radical innovations from initial concept to mass-market commercialization. We find that these innovations were developed over an average of at least 50 years and divide this long development period into four distinct stages—conceptualization, gestation, early incubation, and late incubation. We find that the duration of a stage is longer when different firms lead product development at the beginning and end of the stage. These changes in product development leaders happen frequently, e.g., 76% of firms that were first to commercialize an innovation failed to launch it in the broader market. We also find that the time-to-takeoff for a product category is significantly related to the duration of the preceding late incubation stage. In addition, we find four different ways in which radical innovations borrow from prior seemingly unrelated innovations. We report many other findings on when (duration times), by whom (product development leaders), and how (technology borrowing) radical innovations are developed.

Key words: innovation; new product research; high-tech marketing; product development; speed-to-market; radical innovation; really new products
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Introduction

Innovation is a primary determinant of company success and consumer welfare (Shugan 2007, Solow 1957). Thus, companies devote billions of dollars each year to researching and developing new products. Although many new products generate modest increases in consumer benefits, others are responsible for creating entire new industries and dramatically enhancing living standards. As a result of their importance, these major innovations have been the focus of myriad academic investigations over many decades (see Garcia and Calantone 2002, Gatignon et al. 2002, and Hauser et al. 2006 for overviews). Today, few of us can imagine living without these radical innovations—automobiles, computers, televisions, air conditioners, microwave ovens, cell phones, etc. Yet many important questions remain unanswered about how these innovations were developed.

One stream of research on radical innovation stresses the importance of discontinuities, individual inventors, or sudden breakthroughs (Agarwal and Bayus 2002; Chandy and Tellis 2000; Christensen 1997; Golder and Tellis 1993, 1997; Henderson 1993; Mokyr 1990; Tushman and Anderson 1986; Utterback 1994). These studies focus primarily on the types of firms that introduce innovations, the market response to those innovations, or technological development in the post-commercialization period. As such, this stream of research takes the innovation as given at the time of commercialization, but does not investigate the precommercialization period.

A second stream of research, primarily from a sociological or historical perspective, discusses the development of radical innovations in more evolutionary or organizational terms (Barnett 1953; Basalla 1988; Diamond 1999; Gilfillan 1935a, b; Hargadon 2003; Jewkes et al. 1958; Leifer et al. 2000; Nayak and Ketteringham 1994; O'Connor and Ayers 2005; O'Connor and Veryzer 2001; Ogburn 1922; Rice et al. 1998, 2002; Usher 1954; Veryzer 1998, 2005). These researchers mainly describe the process resulting in radical innovations. While these studies provide rich details on the development of several important innovations and conclude that product development tends to be evolutionary, they also focus on older innovations (e.g., the wheel, ships, stone tools, cotton gin) or case histories of newer innovations (e.g., radio, transistor, Reebok Pump sneaker).

We believe that current research on radical innovations suffers from three key limitations. First, large-sample studies start with innovations in their commercialized forms, thus providing limited insights about their development prior to commercialization.[1] Second, small-sample studies provide rich details, but do not allow us to investigate patterns during the precommercialization period. For example, three influential studies are based on 3–5 industries (Anderson and Tushman 1990, Tushman and Anderson 1986, Utterback 1994). Third, as a consequence of the first two limitations, researchers have not fully addressed interinnovation relationships in the development of radical innovations.

To address these limitations, we compile a comprehensive data set on 29 radical innovations, focusing on the precommercialization period. Our data enable us to address six important questions that have not been answered in previous research.

1. What is the duration of the precommercialization development of radical innovations?
2. How do these durations break down into different stages of development and how have the durations of these stages changed over time?
3. Is the length of one stage related to the length of subsequent stages?
4. What percentage of companies or individuals lead the development of a radical innovation throughout its stages of development?
5. If one company or individual leads throughout the stages of development, will this leadership be associated with shorter or longer development times?
6. Do radical innovations borrow from preceding radical innovations?

An Organizing Framework for the Precommercialization Period

A large body of research reaches a strong consensus about the key events in developing innovations (see Crawford and DiBenedetto 2006, Urban and Hauser 1993 for references). Our framework builds on this consensus by proposing that there are three key events in the precommercialization of radical innovations: *first concept*, *first prototype*, and *commercialization*. We name the three stages culminating in these events *conceptualization*, *gestation*, and *incubation*.[2] These three events and three stages constitute *Precommercialization Product Development*. We use biological terminology for the precommercialization period because it integrates easily with the product life cycle terminology of the post-commercialization period. Many marketing studies consider commercialization (e.g., Agarwal and Bayus 2002; Chandy and Tellis 2000; Golder and Tellis 1993, 1997, 2004; Kohli et al. 1999) and a few also mention first prototype or invention (e.g., Agarwal and Bayus 2002, Golder and Tellis 1993, Kohli et al. 1999), but they tend not to consider first concept (exceptions include Durgee et al. 1998; Griffin 1993, 1997).

During the conceptualization stage, individuals or groups think about potential solutions to market needs or opportunities to use new technologies. Given the preliminary nature of innovations during this stage, at least some of this period involves conceptualizations related to a general problem rather than the solution for a specific application. For example, Edison at first believed that the phonograph would be used for recording business conversations, rather than for listening to recorded music. The culminating event of the conceptualization stage is the development of the first concept. To stay outside the realm of science fiction, we restrict *first concept* to those ideas incorporating the eventual prototype technology. The individual (or group) developing the first concept is the *concept pioneer*.

During gestation, individuals (or groups) apply engineering, scientific, and design principles to develop a working prototype that solves, at least partially, a market need related to the first concept. The culminating event of the gestation stage is the first prototype. The individual (or group) developing the first prototype is the *prototype pioneer*.

During incubation, a prototype is refined through additional application of engineering, scientific, and design principles to improve its functionality until a working model eventually provides enough utility that it can be sold to a customer. The culminating event of incubation is commercialization. The individual (or group) first commercializing an innovation is the *commercialization pioneer*. To be classified as commercialization, the innovation must be purchased, not just used, by an independent party.

Method

Sample

We restrict our investigation to radical innovations for two main reasons. First, radical innovations are more important to companies and societies because of their ability to create entire new industries and destroy existing ones. Second, we believe that companies know more about incremental innovations because they develop scores of innovations of this kind, thus allowing compilation of common characteristics. However, development of radical innovations is distributed across many firms and time periods.

[1] A recent paper by Toubia and Flores (2007) describes a method of screening new product ideas.

[2] Other researchers refer to the process of conceptualization within a given firm as part of the fuzzy front end, and the gestation phase as development or development and testing.

Research on radical innovation has coalesced around two definitions. One requires an innovation to have a "substantially different core technology and provide substantially higher customer benefits relative to previous products in the industry" (Chandy and Tellis 2000, p. 2; Leifer et al. 2000). The second requires advancing "the price/performance frontier by much more than the existing rate of progress" (Gatignon et al. 2002, p. 1107; Leifer et al. 2000). The common element in these definitions is much higher product performance leading to substantially higher customer benefits. Therefore, in our study, we define radical innovations as new products that provide substantially higher customer benefits relative to previous means of providing similar benefits. Our reference point is not previous products in an industry because some innovations, like telegraph and radio, created new industries. However, we can compare the benefits of telegraphs against previous means of communications (e.g., mail service) and the benefits of radio against previous means of entertainment (e.g., live performance) and information delivery (e.g., newspapers). The appropriate determination of reference points relates to the widely studied concept of product-market boundaries, which can be difficult to delineate (Day et al. 1979).[3]

To select a sample of innovations consistent with our conceptual definition, we used two criteria. First, we compiled an initial list of radical innovations (sometimes labeled really new products) analyzed or mentioned in previous research. Second, we focus on innovations with substantial new benefits to customers (typically evidenced by high long-term market penetration) and exclude innovations with more modest incremental benefits (e.g., trash compactor, electric can opener, electric blanket, radar detector, and many second-generation innovations like disposable razors and digital answering machines). In our final sample, 26 of 29 innovations overlap with previous studies (Agarwal and Bayus 2002; Chandy and Tellis 2000; Golder and Tellis 1993, 1997; Kohli et al. 1999). The other three (telegraph, ATM, auto navigation system) all have been mentioned as radical innovations in other articles and appear to provide substantially higher new benefits than some of the radical innovations used in several other studies (e.g., electric blanket, electric can opener).[4] Therefore, our sample is consistent with previous research with the caveat that our focus is on innovations with somewhat higher new benefits than those of the average radical innovation considered in previous research.

Data Collection

The primary challenge in accomplishing the objectives of our study was to compile the complete histories of many innovations. This challenge was especially great because we focus on the precommercialization period. Also, we sought to include events occurring anywhere in the world. Our data come from archival records, which we compiled and analyzed by applying the historical method (Golder 2000). This method has been widely applied in many studies of innovation and new product strategy (e.g., Chandy and Tellis 2000, Golder and Tellis 1993, Srinivasan et al. 2004). In this study, our data collection took more than 2,500 hours.

Data

Product Development Pioneers and Milestone Dates

In Table 1, we present the first company or individual to reach the three milestones in precommercialization product development, along with the year of achievement. In a few cases, we list more than one individual or firm because both reached that milestone at almost the same time. We divide the innovations into three time periods: Pre-1900, 1900–1945, and Post-1945, based on the year the innovation was first sold. These periods reflect the advancing stages of economic development under which each innovation was introduced. We also divide commercialization into micro and macro events. In the next section, we describe our rationale for this division. We include information on the first significant patent for each innovation. However, we do not include this event in our conceptual framework because first patents sometimes preceded first prototypes and sometimes followed them. Also, without more extensive technology data, it is difficult to specify a universal measure for classifying *significant* patents.

Broadening the Concept of Commercialization

Commercialization occurs when an innovation is first sold to a customer. Previous studies have used introduction (Golder and Tellis 1997) and pioneer (e.g., Golder and Tellis 1993, Robinson and Fornell 1985, Urban et al. 1986) to describe this event; however, the most common term in recent studies is commercialization (Agarwal and Bayus 2002, Chandy and Tellis 2000, Golder and Tellis 2004). Kohli et al. (1999) use the word launch somewhat differently, by defining it as the year in which substantial sales begin.

When we compare our commercialization dates with commercialization dates in previous studies, we

[3] See Golder and Tellis (1993) for additional references and a discussion of the challenges of conducting longitudinal research on new product markets using customer-based definitions of product categories.

[4] Later, we evaluate the robustness of our results by using only the 26 innovations studied in previous research.

Table 1 Milestone Dates in Precommercialization Product Development and First Firm or Individual to Reach Milestone

	First concept	First patent	First prototype	Microcommercialization	Macrocommercialization
Pre-1900 innovations					
Telegraph	1753 "C.M." (Unknown writer of letter to a Scottish magazine)	1823 Francis Rolands	1837 Charles Wheatstone/ William Cooke	1838 Charles Wheatstone/ William Cooke	1846 Samuel Morse
Manual typewriter	1714 Henry Mill	1714 Henry Mill	1808 Pellegrino Turri	1854 Pierre Foucald	1878 Remington-Scholes
Refrigerator	1805 Oliver Evans	1834 Francis Perkins	1834 Francis Perkins/ John Hague	1857 Jacob Harrison	1914 GM/Kelvinator
Instant camera	1839 W. H. Talbot	1841 Antoine Claudet	1853 Archer	1864 G. J. Bourdin	1947 Polaroid
Facsimile machine	1843 Alexander Bain	1843 Alexander Bain	1851 Bakewell	1865 Caselli	1966 Xerox/Magnovox
Electric typewriter	1871 Edison	1871 Edison	1880 Edison	1902 Blickendorf	1935 IBM
Telephone	1854 Charles Bourseul	1876 Alexander Bell	1862 Phillip Reis	1876 Alexander Bell	1877 Bell (Alexander Bell)
Phonograph	1877 Charles Cros/ Edison	1877 Charles Cros/ Edison	1877 Edison	1878 Edison	1896 Edison
Air conditioning	1842 John Gorrie	1842 John Gorrie	1844 John Gorrie	1889 Alfred Wolff	1935 York/Kelvinator
Automobile (gas powered)	1860 Etienne Lenoir	1860 Etienne Lenoir	1862 Etienne Lenoir	1889 Benz	1902 Randolph Olds (Oldsmobile)
1900–1945 innovations:					
Radio	1890 Richard Threlfall	1896 Marconi	1895 Marconi	1901 Marconi	1921 RCA/Westinghouse
Washing machine	1906 Nineteen Hundred Washer Co. /O. B. Woodrow	1906 O. B. Woodrow	1906 Nineteen Hundred Washer Co.	1906 Nineteen Hundred Washer Co.	1908 Hurley Machine Co. (Alva Fisher)
Answering machine	1898 Poulsen	1898 Poulsen	1898 Poulsen	1909 Poulsen/Dutch Production Co.	1971 Casio
Auto navigation system	1909 J. B. Rhodes	1909 J. B. Rhodes	1910 Chadwick	1910 Chadwick	1990 Blaupunkt
B&W television: Mechanical	1884 Paul Nipkow	1884 Paul Nipkow	1923 John L. Baird	1928 John L. Baird	1930 John L. Baird
Tape recorder	1888 Oberlin Smith	1928 Ludwig Blattner	1929 Ludwig Blattner	1932 Ludwig Blattner	1963 Phillips
B&W television: Electronic	1908 A. A. Campbell Swinton	1911 A. A. Campbell Swinton	1927 Philo T. Farnsworth	1938 Dumont/ Paramount[a]	1939 RCA/GE/Philco/ Dumont
Post-1945 innovations:					
Microwave	1944 Federal Telephone & Telegraph	1946 Raytheon	1946 Raytheon	1947 Raytheon	1967 Raytheon
Dot matrix printer	1937 Joseph Loop	1937 Joseph Loop	1949 IBM	1949 IBM	1971 Centronics
Color television	1885 A. A. Polumordvinov	1898 A. A. Polumordvinov	1929 John Baird	1951 CBS	1954 RCA
Videotape recorder	1948 Ampex	1950 Ampex	1951 Ampex	1956 Ampex	1972 Cartrivision

Table 1 (Cont'd.)

	First concept	First patent	First prototype	Microcommercialization	Macrocommercialization
ATM	1957 Luther Simjian	1957 Luther Simjian	1960 Luther Simjian	1967 De La Rue Instruments	1969 Docutel
Cell phone	1947 Bell	1973 Motorola	1966 Bell	1969 Bell	1984 Motorola
Post-1945 innovations:					
Calculator (pocket)	1966 Texas Instruments	1967 Texas Instruments	1967 Texas Instruments	1970 Casio (which licensed TI's design)	1971 Bowmar
PC	1970 Intel	1971 Intel	1974 Scelbi	1974 Scelbi	1975 MITS
Laser printer	1968 Xerox	1971 Xerox	1973 Xerox	1975 IBM	1975 IBM
Digital camera	1972 Texas Instruments	1972 Texas Instruments	1975 Kodak/Fairchild	1976 Fairchild Semiconductor	1986 Canon
PDA	1975 Satyan G. Pitroda	1975 Satyan G. Pitroda	1978 Toshiba	1980 Toshiba	1986 Psion
CD player	1962 Minnesota Mining Co.	1962 Minnesota Mining Co.	1974 Philips	1983 Philips/Sony	1983 Philips/Sony

[a]Dumont was a partial subsidiary of Paramount.

find that our dates tend to precede other studies' dates by several years. As a result, we reconceptualize commercialization into two events: *microcommercialization* and *macrocommercialization*. Accordingly, we divide the incubation stage into *early incubation* and *late incubation*. Early incubation is the period from first prototype to microcommercialization. Late incubation is the period from microcommercialization to macrocommercialization. This stage coincides with the first portion of the product life cycle's introduction stage, which continues until sales takeoff.

Our conceptual and operational definition of microcommercialization is the same as previous studies' definition of commercialization, i.e., the first sale of an innovation. Our conceptual definition of macrocommercialization is the first year a firm sells the innovation to a broad market. Our operational definition of a broad market is annual sales of at least 10,000 units.[5] Macrocommercialization typically occurs many years before sales takeoff, when average sales are nearly 1 million units (Golder and Tellis 2004).

[5] A firm's sales at microcommercialization and macrocommercialization can be to either businesses or individual consumers because our research focuses on product development and its relationship with overall market response to innovations. We present information on sales to businesses versus individual consumers for each innovation in the appendix, and evaluate the potential impact of these different markets on our results in the Technical Appendix, available at http://mktsci.pubs.informs.org.

In Table 2, we present a comparison of our dates for microcommercialization and macrocommercialization with the dates for similar concepts in previous studies. As expected, our dates for microcommercialization precede the dates for first sales in other studies by 3–21 years, on average. An important implication of this finding is that the introduction stage of the product life cycle is considerably longer than has been identified in previous studies. However, some of these studies examine consumer markets only, and our microcommercialization dates reflect the first sale to either consumers or businesses. Our dates for macrocommercialization are 1–20 years later than the commercialization dates in other studies. Those studies, with a small difference from our macrocommercialization dates, appear to identify commercialization as the start of sales to a broad market. Therefore, although studies have tended to agree on the conceptual definition of commercialization, its operational measurement seems to have shifted between our concepts of microcommercialization and macrocommercialization.

Borrowing from Previous Innovations

To address one of our research questions, we investigate interrelationships between each radical innovation and those radical innovations within our sample that preceded it. We consider four classes of potential

Table 2 Comparison of Dates for Microcommercialization, Macrocommercialization, and Similar Concepts in Other Studies

	This study: Microcommercialization	This study: Macrocommercialization	Golder/Tellis 1993: Market pioneer	Golder/Tellis 1997: Introduction	Chandy/Tellis 2000: Commercialization	Kohli et al. 1999: Launch	Agarwal/ Bayus 2002: Commercialization:
Manual typewriter	1854	1878			1872		
Refrigerator	1857	1914		1918	1851	1913	
Instant camera	1864	1947	1864		1864		
Facsimile machine	1865	1966	1964		1865		
Telephone	1876	1877	1877		1876		
Phonograph	1878	1896			1878		1897
Air conditioning	1889	1935		1929	1902	1933	1935
Automobile	1889	1902		1898	1888		1890
Radio	1901	1921		1920	1897	1922	1919
Electric typewriter	1902	1935			1902		
Washing machine (electric)	1906	1908			1908	1910	1921
Answering machine	1909	1971		1972	1903		
B&W television (mechanical)	1928	1930			1930		
Tape recorder	1932	1963			1934		1952
B&W television (electronic)	1938	1939		1939	1939	1939	
Microwave	1947	1967	1966	1966	1953	1955	1970
Printer: Dot matrix	1949	1971			1953		
Color television	1951	1954	1954	1954	1954	1954	
Videotape recorder	1956	1972	1963	1972	1956	1975	1974
Cell phone	1969	1984		1983	1983	1983	1983
Calculator (pocket)	1970	1971		1971	1971	1972	
PC	1974	1975	1975		1975	1975	1974
Printer: Laser	1975	1975			1976		
Digital camera	1976	1986			1983		
PDA	1980	1986			1993		
CD player	1983	1983		1983	1979	1983	1983
Average difference (This study's microcommercialization dates minus other studies' dates)			−18.6	−20.5	−2.6	−14.4	−15.8
Average difference (This study's macrocommercialization dates minus other studies' dates)			13.6	0.7	20.0	0.8	0.7

links: shared core technology, shared ancillary components, shared functionality or application, and shared look-and-feel. Core technology is the central technology on which an innovation is based. For example, PCs rely on microprocessors and CD players rely on lasers. Ancillary components are supporting technologies and mechanisms that contribute to the functioning of the innovation. For example, color TVs used vacuum tubes similar to those used in previous innovations. Functionality relates to the market need that an innovation satisfies. Sometimes the form of two innovations can be very different, yet the market need being satisfied is nearly the same. For example, telegraphs and telephones both satisfy a communication need. Finally, shared look-and-feel describes similarities across innovations in how consumers view and interact with them. For example, early PDAs were very similar to calculators. Our measures for each of the four types of borrowing are the total number of links between the target innovation and all other innovations in our sample.

Results

Our data set identifies product development pioneers, the years all milestones were achieved, and links to previous innovations in our sample. In Table 3, we present correlation matrices for the set of variables resulting from our data over the three precommercialization stages plus the period from macrocommercialization to takeoff. We use proportional hazard models to evaluate the relationship between duration of each development stage and several variables (see Table 4). We include the starting year of a stage to examine whether the duration of the development stage has decreased over time. Duration of the *previous* stage allows us to evaluate whether this variable is positively or negatively related to the duration of the current stage. Leadership persistence may also affect duration times because persistent leaders may be strong firms that also have the financial and technical resources to shorten development stages. We measure leadership persistence as a categorical variable (1 = persistence; 0 = no persistence), which occurs when the product development leader at the duration's beginning milestone (e.g., first prototype) is the same as the product development leader at the duration's ending milestone (e.g., microcommercialization). Greater borrowing from previous innovations may shorten durations by reducing the amount of incremental development work required. Our total

Table 3 Correlation Matrices for Durations 1–4

	Persistence1	Duration1	StartYear1	Total borrowing	RealGDPGrowth1	
Duration 1 (Gestation: Concept to prototype)						
Persistence1	1					
Duration1	−0.4028	1				
StartYear1	0.2078	−0.7012	1			
Total borrowing	0.0862	−0.2589	0.6577	1		
RealGDPGrowth1	0.2677	−0.0673	−0.0751	−0.0638	1	
	Persistence2	Duration2	StartYear2	Total borrowing	RealGDPGrowth2	Duration1
Duration 2 (Early incubation: Prototype to microcommercialization)						
Persistence2	1					
Duration2	−0.6949	1				
StartYear2	0.4911	−0.6481	1			
Total borrowing	0.2281	−0.3501	0.7145	1		
RealGDPGrowth 2	−0.2969	0.2938	−0.2798	−0.0015	1	
Duration1	−0.1320	0.3361	−0.4283	−0.2589	−0.0513	1
	Persistence3	Duration3	StartYear3	Total borrowing	RealGDPGrowth3	Duration2
Duration 3 (Late incubation: Microcommercialization to macrocommercialization)[a]						
Persistence3	1					
Duration3	−0.3563	1				
StartYear3	0.1325	−0.5215	1			
Total borrowing	−0.0686	−0.2800	0.7297	1		
RealGDPGrowth3	−0.2663	0.2700	−0.3892	−0.0576	1	
Duration2	−0.1850	0.2242	−0.4711	−0.3501	0.1248	1
		Duration4	StartYear4	Total borrowing	RealGDPGrowth4	Duration3
Duration 4 (Late introduction: Macrocommercialization to takeoff)						
Duration4		1				
StartYear4		−0.5933	1			
Total borrowing		−0.4203	0.7215	1		
RealGDPGrowth4		−0.0308	0.3158	0.2553	1	
Duration3		0.4510	−0.2166	−0.2021	−0.1218	1

[a]This stage overlaps with a portion of the introduction stage of the product life cycle. Thus, we divide the introduction stage into early introduction and late introduction, using macrocommercialization as the dividing event. Early introduction is the same period as late incubation, with the former term emphasizing market development and the latter term emphasizing product development.

borrowing measure is the sum of the measures for the four types of borrowing (e.g., core technology, shared components, etc.). Finally, we include real annual GDP growth to evaluate whether the general economy might be related to these durations. The proportional hazard model enables us to use a time-varying measure for GDP growth.

We use logit models to evaluate the relationship between leadership persistence and several variables (see Table 5).[6] We include the year each stage began and real GDP growth over the course of the stage for the same reasons noted above. The GDP measure is the geometric mean of the annual growth rates across the duration of each period. Duration of current stage allows us to consider the possibility that shorter (longer) stages make it inherently easier (harder) for leaders to persist. Borrowing from previous innovations could either increase leadership persistence because it simplifies development or it could decrease leadership persistence because other firms with related capabilities could overtake the current leader.[7]

Although our models examine the associative nature of the relationships between each dependent variable and several other variables, they cannot prove causal relationships. We speculate about potential causal relationships as the basis of our model

[6] We use ln(years) in the logit model to control for outliers. The hazard model has a nonlinear functional form.

[7] We thank the associate editor and an anonymous reviewer for suggesting that three other variables, new category versus within category radical innovations, sales to businesses versus individual consumers at microcommercialization, and sales to businesses versus individual consumers at macrocommercialization, may have an impact on our results. However, these three variables do not have a significant impact on duration or leadership persistence, nor do they affect the conclusions from the models' primary variables. A data table of these variables is in the appendix.

Table 4 Hazard Model Results for Duration of Stages[a]

	Start year	Previous stage duration	Persistence of leader[b]	Borrow from previous innovations	Real GDP growth	Log likelihood	U^2
Duration of gestation	**0.010***** **(0.0037)**					−67.46	0.068
			1.21*** **(0.43)**			−68.31	0.051
				0.076 (0.10)		−72.15	0.0038
					0.050 (0.051)	−67.5	0.0069
	0.018*** **(0.0061)**		**1.26***** **(0.50)**	**−0.54***** **(0.18)**	0.058 (0.058)	−59.10	0.13
Duration of early incubation	**0.017***** **(0.0051)**					−66.21	0.096
		−0.014 (0.0096)				−71.81	0.019
			2.28*** **(0.60)**			−63.45	0.12
				0.21* **(0.11)**		−71.40	0.025
					−0.072** **(0.035)**	−71.32	0.026
	0.015** **(0.0072)**	−0.0039 (0.010)	**1.52**** **(0.67)**	−0.088 (0.15)	−0.037 (0.037)	−60.71	0.17
Duration of late incubation	**0.019***** **(0.0062)**					−66.53	0.076
		−0.016 (0.017)				−71.51	0.0073
			1.18** **(0.49)**			−69.46	0.036
				0.15 (0.10)		−71.41	0.0087
					0.020 (0.040)	−71.91	0.0017
	0.025** **(0.010)**	0.020 (0.019)	0.93 (0.65)	−0.072 (0.19)	0.014 (0.042)	−63.92	0.11
Duration of late introduction	**0.025**** **(0.012)**					−29.00	0.089
		−0.022 (0.015)				−30.57	0.039
				0.21 (0.13)		−30.52	0.041
					0.0016 (0.043)	−31.82	0.000
	0.043** **(0.018)**	**−0.037**** **(0.018)**		−0.19 (0.23)	0.031 (0.054)	−26.31	0.17

Notes. Standard errors are in parentheses; $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.10$. Parameters in bold are statistically significant.

[a]When we pool data across the first three stages, start year and persistence of leader maintain their sign and high significance levels in univariate and multivariate hazard models (start year: 0.011, $p < 0.01$ and 0.015, $p < 0.01$; persistence of leader: 0.91, $p < 0.01$, and 1.13, $p < 0.01$). Also, borrowing from previous innovations is positive and significant (0.11, $p < 0.05$) in a univariate hazard model, providing some evidence that higher borrowing is associated with an increased hazard and shorter duration.

[b]We do not include this variable in modeling duration of late introduction because the end of this stage (takeoff) is primarily a market development milestone rather than a product development milestone. Thus, in most cases, it is not possible to attribute this event to a single firm.

specification. We then elaborate on the significant relationships to answer, in part, the six research questions posed in the Introduction.

What Is the Duration of the Precommercialization Period and Its Stages?

Table 6 presents the duration of the stages in the precommercialization period, including microcommercialization to macrocommercialization because this period of development precedes an innovation's suitability for a broad market. Summing across the three stages, the duration from first concept to macrocommercialization is 50 years, on average, with a median duration of 25 years.[8] Even in more recent innovations, this average period lasts 22 years, with a median of 10.5 years. These long durations suggest that new products are not invented in a moment, but require continuous development over decades. For example, fax machines were sold as early as 1865, yet consumer benefits were insufficient for wide-scale adoption until the 1980s. Even for post-1945 innovations, it takes almost five years of development to turn a prototype into a product that is sold. Then, it takes an additional eight years to make the innovation suitable for a broad market of customers.

Have the Durations of the Precommercialization Stages Changed over Time?

Table 6 reports the durations of the stages for three time periods. These stages tend to shorten over time. In fact, all three stages are significantly shorter for post-1945 innovations than for pre-1900 innovations ($p < 0.10$, $p < 0.05$, and $p < 0.05$ for gestation, early incubation, and late incubation, respectively). More important, the hazard model results indicate that the starting calendar year is significantly related to all four durations (see Table 4). Positive coefficients mean that higher calendar years increase the hazard, leading to shorter durations. If we focus more narrowly

[8] For consistency with Table 6, we report the sum of the three stages' median durations.

Table 5 Logit Model Results for Persistence of Leadership Across Stages[a]

	Start year	Stage duration (Ln years)	Borrow from previous innovations	Real GDP growth	Constant	Likelihood ratio (Chi-squared)
Persistence during gestation	0.007 (0.007)				−14.515 (12.886)	1.33
		−1.110** **(0.443)**			**1.309*** **(0.774)**	9.70
			0.093 (0.201)		−0.731 (0.649)	0.22
				31.813 (22.998)	**−1.871*** **(1.082)**	2.10
	−0.013 (0.014)	**−1.481**** **(0.629)**	0.477 (0.403)	17.106 (25.384)	24.897 (26.518)	12.04
Persistence during early incubation	**0.023**** **(0.009)**				**−42.949**** **(17.856)**	7.47
		−2.284*** **(0.827)**			**4.575**** **(1.776)**	21.23
			0.256 (0.212)		−0.274 (0.630)	1.55
				−33.769 (22.974)	1.551 (0.978)	3.59
	0.001 (0.022)	**−2.169**** **(0.974)**	0.093 (0.449)	−5.446 (32.184)	3.136 (42.213)	21.36
Persistence during late incubation	0.007 (0.010)				−15.187 (19.889)	0.52
		−0.828** **(0.363)**			0.311 (0.694)	6.87
			−0.085 (0.232)		−0.937 (0.699)	0.14
				−30.385 (22.750)	−0.346 (0.724)	1.86
	0.002 (0.020)	**−0.955**** **(0.469)**	−0.361 (0.465)	4.949 (29.354)	−3.062 (37.472)	8.01

Notes. Standard errors are in parentheses; $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$. Parameters in bold are statistically significant.
[a]We use probit models to evaluate the robustness of our logit model results. In all cases, significant variables maintain their sign and significance levels. Also, when we pool data across the three stages and estimate a multivariate, random-effects logit model, the parameter for stage duration maintains its sign and increases its significance level (−1.241, $p < 0.01$).

on the six categories microcommercialized since 1970, the three stages continue to shorten (4.7, 2.8, and 3.0 years, on average).

Is the Length of One Stage Related to the Length of Subsequent Stages?

The correlations between durations of gestation and early incubation and between durations of late incubation and late introduction (i.e., macrocommercialization to takeoff) are positive and reasonably high (see Table 3). Although hazard model results (Table 4) are consistent with these correlations, the coefficients on previous stage for durations of early incubation and late introduction, when considered separately, are not statistically significant ($p = 0.14$ in both models). Yet the coefficient in the full model for the duration of late introduction is significant ($p < 0.05$). This negative coefficient indicates that a longer stage of late incubation is associated with a reduced hazard and longer time to takeoff.

To further investigate whether the late incubation stage is related to takeoff, we use the duration of late incubation to predict the time from macrocommercialization to takeoff. For this analysis, we use the 16 categories that overlap between our study and Golder and Tellis (1997) or Agarwal and Bayus (2002) (see Table 2). In the two cases where these studies do not agree on takeoff dates, we use the average of their dates. When we regress the time between macrocommercialization and takeoff versus the duration of the late incubation stage, the slope parameter is positive and marginally significant ($p = 0.08$). Moreover, when we use the regression equation to predict the time to takeoff, the average absolute margin of error is a reasonably small 3.7 years.[9]

What Percentages of Companies or Individuals Lead the Development of a Radical Innovation Throughout Its Stages of Development?

Table 7 presents the number of product development leaders at each stage who persist with their leadership at the next stage. In those cases with more than one individual or firm at a milestone, the results in Table 7 are based on treating such coleadership the same as sole leadership. To interpret this table, each row should be considered separately. The sample for the first row is all concept pioneers. The samples for the second and third rows are, respectively, all prototype pioneers and all microcommercialization pioneers. The numbers in the table indicate the number of pioneers in each sample that also led product development at the subsequent milestone. For example, 11 of the firms with first concept also had the first prototype, but only one firm from this sample was also first at macrocommercialization.

These results indicate that it is extremely difficult to maintain leadership across the product development milestones. Moreover, whenever a leader at one milestone loses its leadership at the next milestone, it never regains leadership at a subsequent milestone.

[9] For comparison, the error for forecasts made at commercialization in Golder and Tellis (1997) is 1.9 years; however, the mean time-to-takeoff for their nine categories is 4.1 years. The mean time-to-takeoff in this study is 8.3 years. So, on a percentage basis, the average margin of error is similar with the two approaches (3.7/8.3 = 45%; 1.7/4.1 = 41%).

Table 6 Average and [Median] of Stages in Years (Standard Deviation)

Stage	End milestone	All categories	Pre-1900 ($n=9$)	1900–1945 ($n=8$)	Post-1945 ($n=12$)
Conceptualization	First concept	Start date for this stage is indeterminate.			
Gestation	First prototype	16.1 [5] (23.8)	26.8 [8] (36.4)	14.3 [7] (17.1)	9.3 [3.5] (12.2)
Early incubation	Microcommercialization	10.2 [5] (12.5)	20.2 [14] (16.7)	7.3 [5.5] (7.3)	4.6 [2.5] (6.1)
Late incubation	Macrocommercialization	23.4 [15] (28.0)	39.0 [24] (35.2)	28.9 [25.5] (29.4)	8.0 [4.5] (8.2)

Interestingly, the unconditional probability of persisting as the leader does not appear to differ from the probability conditional on persisting in leadership during the previous stage. For example, 59% of prototype pioneers (17 of 29) go on to be microcommercialization pioneers. Yet among prototype pioneers who were also concept pioneers, the percentage is nearly the same (55% or 6 of 11). Similarly, 24% of microcommercialization pioneers (7 of 29) go on to become macrocommercialization pioneers, yet among microcommercialization pioneers who were also prototype pioneers, the percentage is the same (24% or 4 of 17). These results suggest that the skills necessary to succeed in one stage are different from the skills necessary to succeed in a later stage.

Is Product Development Leadership Persistence Associated with Shorter or Longer Stages?

Table 5 shows the logit model results relating persistence to duration and several other variables. Leadership persistence is negatively related to stage duration. This result is consistent for all three persistence models, whether we consider duration alone or as part of the full model. Similarly, hazard model results show a strong negative association between leadership persistence and duration. Table 8 confirms the strong negative relationship between leadership persistence and duration time. One possible explanation for this result is that innovations vary in their inherent difficulty to develop. Easier innovations will be developed more quickly and leaders will tend to persist across these shorter stages. However, with more difficult innovations, economic payoffs may be far in the future. Therefore, leaders may reduce or eliminate their investments, creating opportunities for other firms to capture leadership before the next milestone. Moreover, even if leaders face a constant hazard rate, shorter stages will be associated with higher leadership persistence.

Do Radical Innovations Borrow from Preceding Radical Innovations?

The concept of a radical or discontinuous innovation suggests a sharp break from previous innovations. We now use our data to consider whether radical innovations are linked to preceding radical innovations, at least within our sample of 29 innovations. As discussed previously, we propose four types of potential links: shared core technology, shared ancillary components, shared functionality or application, and shared look-and-feel.

Most of the innovations in our sample (59%) use a core technology that has been used in at least one previous innovation. In fact, several innovations use core technologies that have been used in multiple previous innovations. Among innovations using an existing core technology, those core technologies had been used in 1.6 previous innovations, on average. At the component level, product developers often include elements that are remarkably similar to those that were developed decades before. For example, the printing mechanism of late-generation printing telegraphs is very similar to that of modern inkjet printers. Similarly, the earliest patent for an electric typewriter used a piano-like keyboard and a typewheel design consisting of two synchronized revolving cylinders. Both of these elements were borrowed from an early prototype of the printing telegraph built years earlier. In our sample, 20 of 29 innovations

Table 7 Number of Product Development Pioneers Leading at Subsequent Milestones

Sample	First prototype	Microcommercialization	Macrocommercialization
Concept pioneers ($n=29$)	11	6	1
Prototype pioneers ($n=29$)		17	4
Microcommercialization pioneers ($n=29$)			7

Table 8 Duration of Stages and Product Development Leadership Persistence

Stage	End milestone	Duration without leadership persistence (years)	Duration with leadership persistence (years)
Gestation	Prototype	23	4.0
Early incubation	Microcommercialization	20	3.0
Late incubation	Macrocommercialization	29	6.0

(69%) shared either their core technology or at least one of their components with preceding innovations. The actual level of borrowing is even higher; this percentage includes only links within our sample of 29 innovations.

Shared functionality is important in many of our innovations because they satisfy the same basic needs for entertainment or communication. More specifically, in the one-to-one audio market, cell phones were commercialized more than three decades later than consumer mobile telephone services and almost a century behind commercial mobile telephones, both of which used radios to transmit and receive signals. In one-to-many audio, phones delivered music to a mass audience before radio, thus presaging the mass-communication business model that revolutionized the radio industry. For example, in 1884, an orchestra concert was delivered to subscribers of seven telephone exchanges in Texas (*Electrical Review* 1884). Even after consumer radios were commercialized, the telephone delivered news, weather, and financial reports to rural audiences (Gilliams 1925, Maver 1907).

Finally, a shared look-and-feel is common across many of our innovations. For example, keyboards are used in telegraphs, typewriters, and PDAs. Televisions reflect the look-and-feel of radios, and early cell phones borrowed from landline phones.

Robustness of Model Results

We use several analyses to assess the robustness of our primary results. First, we model the entire duration (gestation, early incubation, late incubation) as a function of start year, persistence propensity, total borrowing, and real GDP growth. Persistence propensity is measured as the sum of persistence of leader across the three periods, so it can take a value from 0–3. Consistent with our expectations, in univariate models we find positive and significant parameters for start year ($p < 0.01$), persistence propensity ($p < 0.01$), and total borrowing ($p < 0.05$), but real GDP growth is not significant. In the multivariate model, the two variables that are consistently significant in Table 4, start year and persistence, maintain their significance ($p < 0.01$ and $p < 0.10$, respectively).

Second, we remove the three categories from our data that have not been included in previous research on radical innovation (telegraph, auto navigation system, ATM). Here, we model each stage's duration as a function of start year, previous stage duration (except for duration of gestation), persistence of leader, total borrowing, and real GDP growth. Start year remains positive and significant for all four durations ($p < 0.01$ in three cases; $p < 0.05$ in one case). Previous stage duration remains negative and significant for duration of late introduction ($p < 0.05$), which is the only stage in which it is significant in Table 4. Persistence of leader remains significant for duration of gestation ($p < 0.05$), drops below statistical significance for duration of early incubation ($p = 0.16$), but becomes statistically significant for duration of late incubation ($p < 0.05$). After dropping these three categories with the logit model, the one consistently significant variable, stage duration, remains significant in all three persistence models ($p < 0.05$).

Third, we consider a nonparametric hazard specification by conducting univariate Wilcoxon tests for the two variables that are consistently significant in Table 4, start year and leadership persistence. In these tests, both variables have the expected sign (negative because this test evaluates duration, rather than the hazard of ending duration) and are significant ($p < 0.05$) across all four durations, plus total duration ($p < 0.01$ in six cases; $p < 0.05$ in three cases; no data on persistence of leader for duration of late introduction).

Fourth, we consider a parametric hazard model specification using a Weibull baseline because this distribution is consistent with the survival function derived from the nonparametric tests. In the multivariate model specification, start year and persistence of leader remain statistically significant for all four durations, plus total duration ($p < 0.01$ in six cases; $p < 0.05$ in two cases; $p < 0.10$ in one case). For duration of late introduction, previous stage duration remains significant ($p < 0.05$). Overall, these robustness checks confirm our primary model results.

Conclusion

Summary of Findings

Previous research has shifted between characterizing the development of innovations as either sudden breakthroughs of individual, genius inventors or the long, painstaking process of many players steadily accumulating incremental knowledge. However, few generalizations exist. Therefore, we use our data on 29 innovations to identify patterns and relationships during precommercialization product development. We now summarize the key empirical results of our study, organized according to when, by whom, and how radical innovations are developed.

When

• The innovations in our sample were developed for 26 years, on average, prior to microcommercialization. It took an additional 23 years, on average, for innovations to be sold to a broad market of customers.

• Even with more recent innovations, the time from first concept to macrocommercialization is over 20 years, on average.

• The time-to-takeoff is many years longer than has been identified in previous research. Although some previous studies operationalized commercialization as macrocommercialization, innovations are actually sold in small quantities many years earlier.

- The time from microcommercialization to macrocommercialization is related to the time from macrocommercialization to takeoff and can be used to make reasonably accurate predictions of the takeoff year.

By Whom

- Only one firm in our study led product development from first concept to macrocommercialization.
- Thirty-eight percent of firms with the first concept also develop the first prototype.
- Fifty-nine percent of firms with the first prototype are also the first to sell the innovation.
- Yet only 24% of firms that are first to microcommercialize an innovation are also first to macrocommercialize it.
- Longer development stages are associated with a change in the firm leading product development at the next milestone.

How

- Many radical innovations borrow from previous innovations in four key ways: core technology, ancillary components, functionality, and look-and-feel.
- Inspiration for some innovations comes from previous innovations that seem unrelated to the current innovation (e.g., early computers and player pianos both used paper to store data).

Implications for Managers

Our study has four key implications for managers. First, managers should be cautious about investing in early stage research on radical innovations. Given the long time between these investments and sales, returns may be low. Therefore, managers should adopt a long-term perspective when developing radical innovations. Second, leadership changes across stages suggest that firms with different skills emerge at different stages of product development. Therefore, a company leading development at an early stage might consider leveraging its current leadership by selling or licensing its technology to a company with different technological capabilities or marketing skills. Third, managers and industry analysts can use the duration of late incubation as one additional predictor of time to sales takeoff. Such predictions are valuable because they can be made many years before takeoff. Moreover, this predictive ability is one benefit of dividing commercialization into micro and macro events because only the duration of late incubation can predict takeoff; the combined durations of early incubation and late incubation cannot predict takeoff. Fourth, companies can take both an engineering orientation toward borrowing from previous innovations by adopting core technologies and components or a marketing orientation by adopting common functionality and a similar look-and-feel. Because most of the radical innovations in our sample borrowed from previous radical innovations, such strategies are likely to be very important in developing future radical innovations.

Directions for Future Research

Our initial step of documenting precommercialization product development has opened up many areas for additional research. We identify six broad opportunities for future research and many research questions within these areas.

First, there are many questions about firm competition prior to commercialization that should be addressed. For example, what factors allow firms to persist as leaders throughout precommercialization product development? How does the relative importance of these factors vary across stages? What is the role of patents in promoting leadership persistence? How many firms tend to compete at each milestone? What happens to firms that lose their leadership? Do they fail or do they achieve a lower level of success? How long do firms maintain their leadership during the various stages?

Second, researchers should further investigate the durations of stages in precommercialization product development and the potential impact of variables like media coverage, technology complexity, technology borrowing, legal or regulatory barriers, compatibility of innovations, and strengths in associated categories (Keller and Lehmann 2006). Also, it will be important to understand whether durations for innovations that fail in the market are different from the successful innovations in our study.

Third, the links between innovations invite more research on the nature of product categories and their boundaries. When do these innovations emerge as distinct product categories? Is the time of such emergence different when the emphasis is on technological characteristics or customer benefits? Also, the prevalence of links between innovations calls for greater understanding of the process by which this information is disseminated. Moreover, expanding the investigation of links beyond the 29 innovations in our sample will provide more general results on technology borrowing.

Fourth, more detailed investigation of core technologies is warranted. How much of their development is done independently of any particular innovation? How quickly are new core technologies developed?

Fifth, future studies could extend our knowledge about precommercialization innovation by moving beyond the durable goods investigated in this study to consider services, nondurable goods, industrial products, pharmaceuticals, and second-generation radical innovations.

Finally, it will be important to investigate consumer knowledge over time. We find that mass-market publications begin to cover many of these innovations long before commercialization. This period of emerging knowledge opens up many questions for future research. For example, how widespread is consumer awareness and knowledge of these innovations prior to commercialization? How active is word of mouth prior to commercialization?

Once future researchers address these questions, companies will have even more information about developing radical innovations and the markets for those innovations. As a result, consumers and society are likely to benefit more quickly and more often from future innovations.

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Appendix
Table A.1 presents our classifications of three variables that could affect duration of stages or leadership persistence. We believe this is the first time these classifications have been reported in the literature. Overall, we find that these new variables are not associated with our dependent variables. Moreover, the significance levels of the variables in our primary specifications hold after including these new variables. Thus, our primary results and conclusions are robust to these inclusions. However, we still recommend further consideration of these potentially important variables with other radical innovations and dependent variables.

Table A.1 Classification of Innovations on Three New Variables

Innovation	New category or within broader category[a]	First sale at microcommercialization	Majority of sales at macrocommercialization
Telegraph	New	Business	Business
Manual typewriter	New	Business	Business
Refrigerator	Unclear	Business	Consumer
Instant camera	Within camera category	Consumer	Consumer
Facsimile machine	Unclear	Business	Business
Electric typewriter	Within typewriter category	Business	Business
Telephone	New	Business	Business
Phonograph	New	Business	Consumer
Air conditioning	Unclear	Business	Consumer
Automobile	New	Consumer	Consumer
Radio	New	Business	Consumer
Washing machine	Unclear	Consumer	Consumer
Answering machine	New	Business	Consumer
Auto navigation system	Unclear	Unclear	Consumer
B&W television (mechanical)	New	Consumer	Consumer
Tape recorder	Within magnetic recording device category	Business	Consumer
B&W television (electronic)	Within television category	Consumer	Consumer
Microwave	Unclear	Business	Consumer
Dot matrix printer	Within electric printing category	Business	Business
Color TV	Within television category	Consumer	Consumer
Videotape recorder	New	Business	Consumer
ATM	New	Business	Business
Calculator	New	Unclear	Consumer
Cell phone	New	Business	Consumer
PC	New	Consumer	Consumer
Laser printer	Within printer category	Business	Business
Digital camera	Within camera category	Business	Consumer
PDA	Within electronic organizer category	Consumer	Consumer
CD player	Within music playback category	Consumer	Consumer

[a]In determining the classifications in this table, we considered whether each innovation's benefits were substantially different from other products within the category, broadly defined. This approach is consistent with our conceptual definition of radical innovation. Also, these determinations were made based on the incremental benefits of these innovations at microcommercialization, rather than a more advanced stage of development.

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