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The evolution of corporate information and communication technology research laboratories

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In this paper we provide an overview of how corporate research has evolved over the recent decades. Our focus is on Information and Communication Technology (ICT) research. We apply broad strokes with the goal to highlight major trends only and will not provide detailed historical overview. We also provide our interpretation of what were and are the major driving forces behind the evolution and why we see a particular trend unfold.

We identify two distinct periods of the evolution of corporate research and innovation laboratories. The first period roughly started at the end of World War II and lasted until the 1980’s, this was the Golden Age of research laboratories. The second phase is the New Age. In between of these two phases there has been a transient period spanning 10-20 years when corporate research laboratories went through a series of organizational and focus changes as the mother company was searching for the best setup and acceptable cost of operating a research organization. Right now we are at the dawn of the New Age.

We describe Golden Age and the New Age of corporate research with the help of a simple PEST analysis (Political, Economic, Social and Technological analysis). Along the analysis we will highlight examples of well-known corporate research labs and how they fit into our model. We correlate the research with Strokes Quadrant model of research. Finally, we show change in theory and practice papers.

The Golden Age (pre 1985)

In the Golden Age, corporate research labs flourished. To better understand why; we review the environment in which they have been established and operated. We present a simple PEST study for the environment. For our context, we define the Political aspect as the attitude of the leadership of the mother company. We use the Economical dimension to refer to the financial strength and focus of the corporation. With Societal aspects we will review the major trend and the directions advocated for research and innovation by the thought leaders of the society as a whole. The Technological dimension will show the maturity of the technology of the ICT industry.

The charismatic leaders and founders of the corporates of the Golden Age are often the inventors of new technologies or processes, like Edison, Bell, Ford, just to name but a few. If we look at CEOs of today's companies, the picture is different. While we do have a few high profile inventors at the helm, most of the firms, especially traditional large corporations have financial experts at the top. There has been a change happening over the century in terms of focus of corporate leadership. We will come back to this point later. **For now, a major political factor of the Golden Age was that technologies have been leading and owning the companies, hence interest and commitment to technological advancement was a given from the very top of the firm.**

One of the best-known corporate research laboratories is Bell Labs [6]. Bell Labs fortune and fame is rooted in the invention of the telephone and the subsequent monopolistic market position of the American Telephone and Telegraph Company (AT&T). AT&T was in a monopoly position until 1984. Another important ingredient of the wealth of AT&T and in corollary Bell Labs, was that the telephony market was in high growth phase, as over the decades millions and millions of new customers were added. These all contributed to a very strong economic position, and spending money on a research laboratory was not a problem, as money was not a scarce resource. A similar pattern can be observed by looking at other famous research laboratories like IBM or Intel. The markets of their products were growing at the time and they were in strong cash position to fund broad research activities. It is clear that research requires a large, long-term investment, and companies with a large market share are more likely to provide such an investment. There is also a different reason why such companies have the best incentive to do such research, illustrated best by a story one of our interviewees relates. He had three job offers from three different research labs, and went to this advisor to get advice on the best choice. His advisor responded by pointing out that research inevitably involves publications, which means that not just the researcher's employer, but also its competitors tend to benefit from the research[1]. But, so long as the employer has the largest market share, it still benefits the most! So, it has the best incentive to support research. Poetically, this advisor was employed by Bell Labs prior to his professorial appointment. **The key economic factor in the Golden Age was a surplus of money in the parent companies.**

Large-scale research laboratories and in particular government funded basic research has its roots in the Office of Scientific Research and Development (OSRD) that was established in 1941 to support the weapon development efforts of the United States and its allies. Based on the success of government funded research combined with the development of the actual weapons by private corporations, President Roosevelt asked Vannevar Bush, head of OSRD, to draft a program that can translate the success of OSRD to peacetime research. The program Bush worked out became the blueprint of government funded research post WWII and later lead to the funding of the National Science Foundation (NSF) [1][2]. Bush's report, titled "Science The Endless Frontier" [1], greatly influenced the separation of basic research from applied research. Bush states in [1] that "Basic research is performed without thought of practical ends. It results in general knowledge and an understanding of nature and its laws", while applied research's role is to take new scientific results and translate it to practical applications. Although some industrial research labs did exists before WWII, like Bell Labs, which was funded in 1925 [6], the flourishing and fame of these laboratories started during and after the war. Hence the idea to provide independence and research freedom to do basic research has been likely influenced by Bush's work. **The basic Societal force in the Golden Age was the wide acceptance of the need and the high esteem of basic research.**

From a technological perspective, the Golden Age, marks the start of the evolution of new technologies and the emergence of new industries and markets. Therefore, there was untapped potential and a large unchartered terrain in front of these companies. The technical needs of the corporations to explore the market and deliver better and better product was inline with the focus of basic research. Basic research discoveries were refined and moved to production. Although not all results were used, but clearly companies benefited from their basic research spending. Just think about the advances of telecommunication over the century, form the telegraph, over long distance telephone, optical communications, and mobile phones. Similarly, silicon technologies and computing underwent a major evolution. Many of the basic research necessary were discovered at the research laboratories. **The major technological factor of the Golden Age was that technology wasn't mature yet, and great research directly drove great societal and financial benefit.**

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[1] Of course, it is possible that the first mover has a temporal advantage to monetize the research and patents help to an extent, but neither really prevents competitors from benefitting.

The New Age

The political, economical, societal and technology landscape of the ICT industry changed significantly over the last 50-60 years. Corporate research laboratories have to adapt to these new realities to stay relevant and oftentimes to fight for their survival. Understanding the current environment in which they have to operate will help to develop a strategy and focus that ensures that the vast knowledge of the research laboratory is properly utilized by the company.

On the Political dimension, the typical competence of corporate leaders changed over the decades. This evolution has been recognized and summarized in [9]: *"Until World War 1, the archetypal CEO in the United States was an engineer or inventor with an orientation towards production. […] In the 1980's, finance-oriented people, adept at valuing firms and increasing the efficiency of the corporate sector through private equity, rose to leadership. […] people more skilled at asset valuation than building products, innovating, and running operations manage most of today's largest U.S. firms. "* This change of competence profile and underlying values and priorities has a profound effect on how basic research and in general longer term innovation activities are valued within corporations. By now traditional large enterprises went through a series of consolidation and the major direction and industry focus areas has become ossified, which limits the ability of a single CEO to dream big and deviate wildly from the core industry. Hence, motivating open ended, Horizon 3 explorations and convincing the board of a company is very difficult today. This goes hand in hand with the established ownership structures and prevailing expectation of predictability, and low risk acceptance of institutional investors, who are the majority of shareholders of today's large enterprises. Since the industry grew to a certain level of maturity, investors want themselves manages risk and diversify their portfolio by investing in firms each of which has preferably a well-defined industry focus. **The Political realities of the New Age are that people with financial background and asset management focus are leading the corporates. The shareholders and the board of the companies prefer a clear industry focus with lean cost structure and low risk.**[2]

As monopoly positions ended and the overall industry matured and consolidated the focus from innovation and technology leadership as the primary competitive advantage shifted to operational efficiency and tight cost management. This shift has been fueled from one end through the change of leadership as noted above but also as market forces drove the revenues and profitability down in the industry. This shift and the resulting scrutiny of expenses directed attention to corporate research laboratories, which being long term focused, had only one clear metric: cost. Since there was no

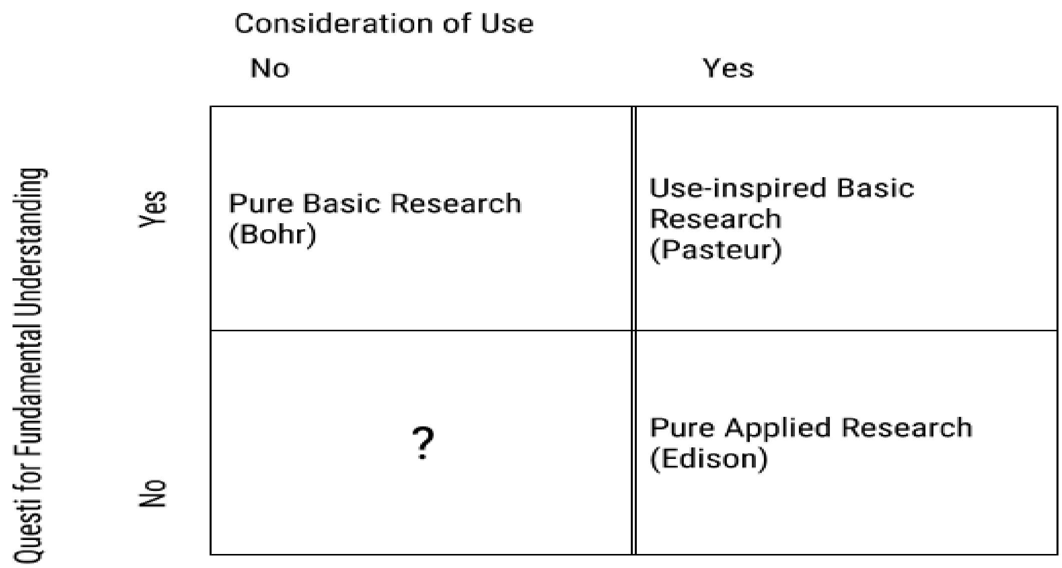
[2] Check the perspective of an interviewee on low risk decisions during tenure at Apple Inc in the Appendix

pressing need before to connect the cost of the laboratory to the actual business outcome and profitability it has became very difficult to provide clear proof points for the high expenses. The problem of corporate research laboratories being cost centers rather than profit and loss responsible organizations has been pointed out by many; for example Randy Katz, a professor of computer science at UC Berkeley, noted that “all industrial research centers are temporary by their very (unprofitable) nature” [1]. As a first step funding for research laboratories has been cut and as a response some activities had to be stopped at the research laboratories. However the overall strategy and structural change necessary only started later. **The Economical environment in the New Age is fierce, there is no more funding available for basic research, or any research for that matter, if the business rationale is not understood and aligned with business strategy.**[3]

The Societal environment changed significantly compared to the Golden Age. One critique of Bush’s program set forth in his report, titled “Science The Endless Frontier”, is Donald Strokes work: “Pasteur’s Quadrant” [3]. Strokes argues that the widely accepted linear model of basic research -> applied research -> development -> production & operation is flawed; one cannot completely disconnect basic research and the subsequent steps from considering practical applications. He devised a quadrant model of research.

Figure: Strokes: Quadrant model of research

[3] Check the research at Microsoft section in the Appendix, Silicon Valley center was downsized



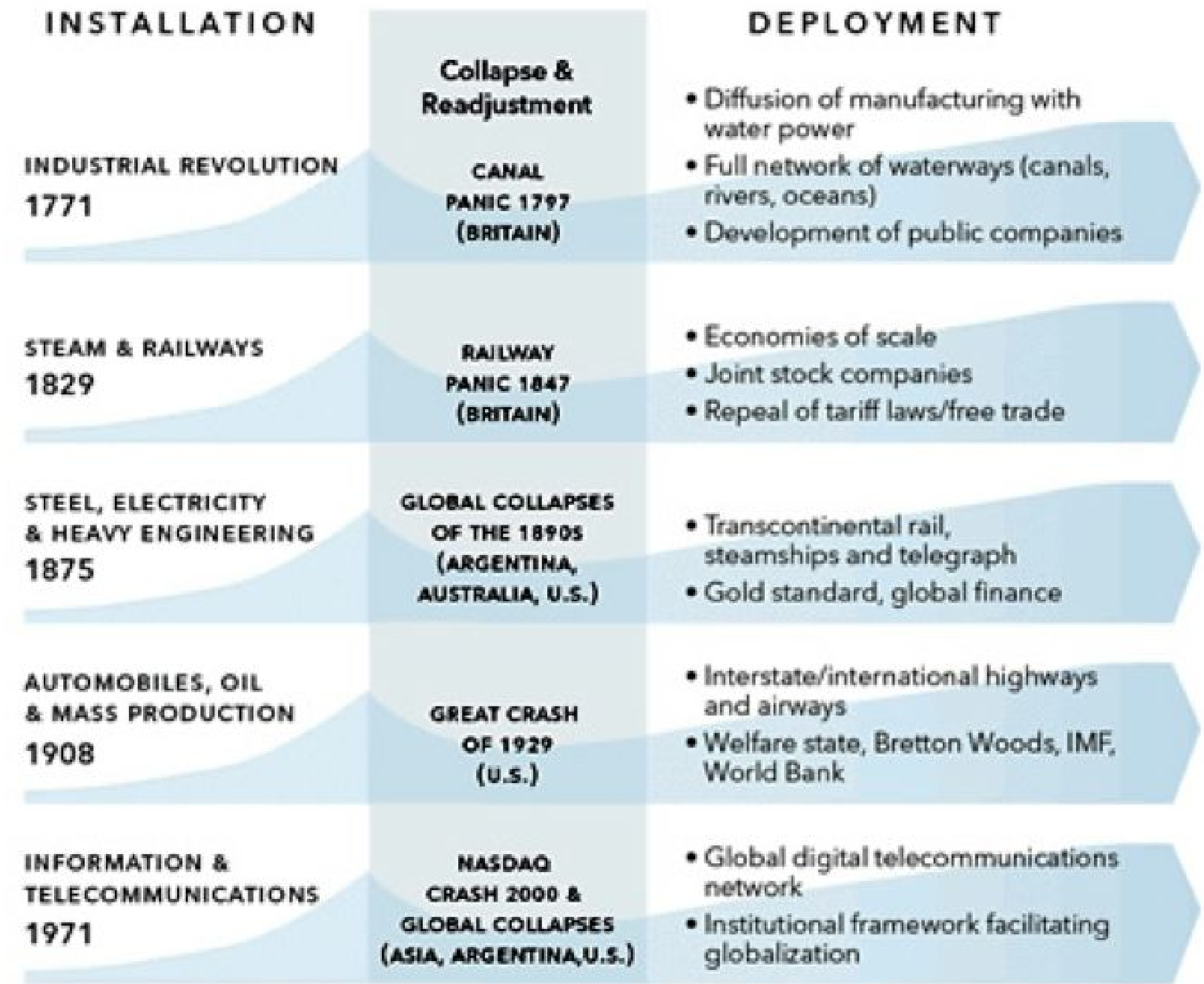
Bohr's Quadrant, represent research with high fundamental value but no practical use at the time of research. Bohr's research to model the structure of the atom is a good example here, it was pure theoretical work. However, over time his findings set the basis of modern disciplines. Edison's Quadrant describes research focused on immediate use, have a market and business goal in mind and conduct research necessary to reach the goals. Pasteur's Quadrant represents work that is driven by a visionary, major practical problem for which fundamental questions need to be answered to arrive to a feasible solution. The remaining unnamed quadrant, the "question mark" research work depicts activities that have no practical and no theoretical relevance. Strokes' quadrant model revealed a simple visualization of research efforts that directed the discussion to the fact that not all research activities are meaningful, i.e., question marks, while also moving forward the argument that application and basic research cannot be separated. Strokes work well illustrates the widely accepted view in the New Age that the scope of corporate research laboratories should be closely aligned with overall corporate strategy.

Another societal trend is that startup founders turned millionaires are the focus of the industry and the frenzy around basic research and theoretical breakthroughs rarely make it into mainstream press. The industry and also individual enterprises moved away for advocating research projects to call out innovation on their agendas. Among many narratives, it is often highlighted that not invention, sort of the goal of basic research, but getting ideas to the market and creating products, the goal of innovation, is important. We also find that in many cases technology does exist but there is no product or business built around the technology, hence focusing on bringing technology to market is of high importance. This highlights a major mindset shift, the desire to focus on business outcomes, instead of interesting experiments. Although moving from research to innovation may seem a changing of the buzzword of the era, it actually is a major conceptual change that needs a very different organizational structure and strategy. Instead of focusing on the technology, innovation programs are more outward facing focusing on market needs and exploring emerging technology together with new business models.

The Societal environment of the New Age values applied, corporate strategy directed research over basic exploratory research. Furthermore, business outcome and new ventures are seen as the desirable research results and not theoretical findings.

The ICT industry has been a fertile ground for technological innovation over the century. Many new technologies from telephony, over radio and optical communications, transistors, integrated circuits, microprocessors, etc. has been invented and developed. Is there anything more left to invent? The answer is certainly, however given the nature of maturing technologies, the speed of change is slowing down, as there are less areas with unexplored breakthroughs, while the marginal improvements of the technologies is getting smaller. In accordance the nature of innovation changes. Carlota Perez's theory of technological revolutions [4] suggests that we are in the deployment phase of the Information and Telecommunication technology revolution. According to Perez's theory, each technological revolution has two phases: installation and deployment.

Figure: Carlota Perez.



During the installation phase the major technology has been proven and the winning architectures selected. Hence most of the research is done for this industrial revolution. The deployment phase is more about the operational aspect of rolling about the technology on a global scale. This suggests that for the New Age a different kind of research focus will be needed; more applied research focus and understanding of practical operational and market dynamics.

Another trend we see in the New Age, is the emergence of product systems. Porter and Heppelmann present in an HBR article [5], how competition is changing in all the industries due to the advancement in ICT. They argue that instead of competing on the product level companies move to add “smart” features as differentiators and then add connectivity to the mix. Connected, smart products are the focus of companies today. However, moving forward the competition will move to the level of the actual intelligence that can take the data, make optimization decisions and control a set of different products in harmony. Porter and Heppelmann call this a product system. The value and competitive advantage will move to the one being able to make use and take control of the physical products. Once these product systems, which are typically a single industry focused evolve to a stable accepted platform, the next step will be to connect these systems and connect individual product systems forming a system of systems. One such example is when a farm management system is connected to seed optimization system, weather data system and irrigation system. This is a very plausible vision given today's technology. However it has an implication on the nature of work expected from corporate research laboratories. In this system setting the questions revolve around what can be learned from the collected data, what industries and practical applications would benefit from a connected product system, what optimizations make sense, which provide value for the customers. All these questions are more market research and business model explorations rather than fundamental technical research questions.

The ability to reach out to many users easily on the Internet has made it possible to run control experiments at unprecedented scale, ensuring great confidence intervals, and even run many overlapping experiments at once[e.g. cf. [4],[5], [6]]; indeed improvements of Internet and web based products such as Facebook, Bing, and Google are driven by such a process. This supplants the role of intuition based, top-down decision making and makes it easier for developers to just "try stuff", turning these products into large laboratories, allowing innovative research not just to happen in Research organizations but also in the Engineering teams. This phenomenon is described in detail in the paper titled Google's hybrid approach to research[7], but is certainly not specific to Google.

There is another New Age trend that reduces reliance on theoretical models to produce practically relevant results for challenging problems. This phenomenon is best described in a paper titled "The Unreasonable Effectiveness of Data"[8]. Quoting: *"when it comes to natural language processing and related fields, we're doomed to complex theories … instead embrace complexity and make use of the best ally we have .. data".* The paper notes that the availability of data and the development of large scale statistical/machine-learning models that are relatively unsophisticated mathematically makes it possible achieve results superior to theoretically -sophisticated approaches. This trend is not specific to natural language processing. Indeed, text processing, voice to speech translation, vision are all

[4] "Overlapping Experiment Infrastructure: More, Better, Faster ..." 2010. 14 Oct. 2015 <http://research.google.com/pubs/pub36500.html>
[5] "PlanOut | A framework for online field experiments." 2014. 14 Oct. 2015 <https://facebook.github.io/planout/>
[6] "Exp Platform." 2006. 14 Oct. 2015 <http://www.exp-platform.com/>
[7] Spector, A. "Google's Hybrid Approach to Research - Research at Google." 2012. <http://research.google.com/pubs/archive/38149.pdf>
[8] Halevy, Alon, Peter Norvig, and Fernando Pereira. "The unreasonable effectiveness of data." *Intelligent Systems, IEEE* 24.2 (2009): 8-12.

increasingly, reliant on large scale machine learning. For instance, this tutorial[9] makes it possible for someone without a PhD in Computer Vision to identify objects within images, something that would have been near impossible a decade ago. The obvious consequence of this trend is less reliance on research (PhDs) and commoditization of certain subfields of computer science.

To summarize, the Technological environment in the New Age is characterized by maturating technologies in the ICT domain and shifting focus to widen the applicability of existing technologies and combine solutions to serve various markets in a more pervasive way.

	Golden Age	New Age
P	technologists at the top	financial background, shareholders, cost, risk
E	monopolistic position, surplus	fierce competition, cost control
S	high esteem of basic research	startup, maker movement
T	new industries, research directly drove societal and financial benefit	maturating technologies in the ICT domain
Horizon	1-2-3	1-2

We now study the evolution of CS research over time in the framework of the four quadrant model[10]. Aspirationally, we would like research to both further understanding, but also be practically relevant, i.e., fall in the Pasteur quadrant. We are going to perform two analyses.

Analyzing CS papers, citations over time

[9] "Torch | Applied Deep Learning for Computer Vision with Torch." 2015. 14 Oct. 2015 <http://torch.ch/docs/cvpr15.html>
[10] "Pasteur's quadrant - Wikipedia, the free encyclopedia." 2012. 20 Oct. 2015 <https://en.wikipedia.org/wiki/Pasteur's_quadrant>

For this analysis, we use data from DBLP[11] and ACM[12], curated by Tang et al.[13]. This dataset contains the list of all CS papers with information about year of publication, the conference of publication and citations.

We classify papers as theory papers if they appear in a specific list of conferences[14]. This list has been sanity checked for precision by three researchers in the area of CS theory, for recall by examining citation patterns across these papers.

Our first observation is straightforward: over time, the fraction of theory papers has decreased significantly as shown by the graph. There are two possible interpretations. That theory plays an increasingly smaller role in the grand scheme of things OR the practice papers have grown more relevant.

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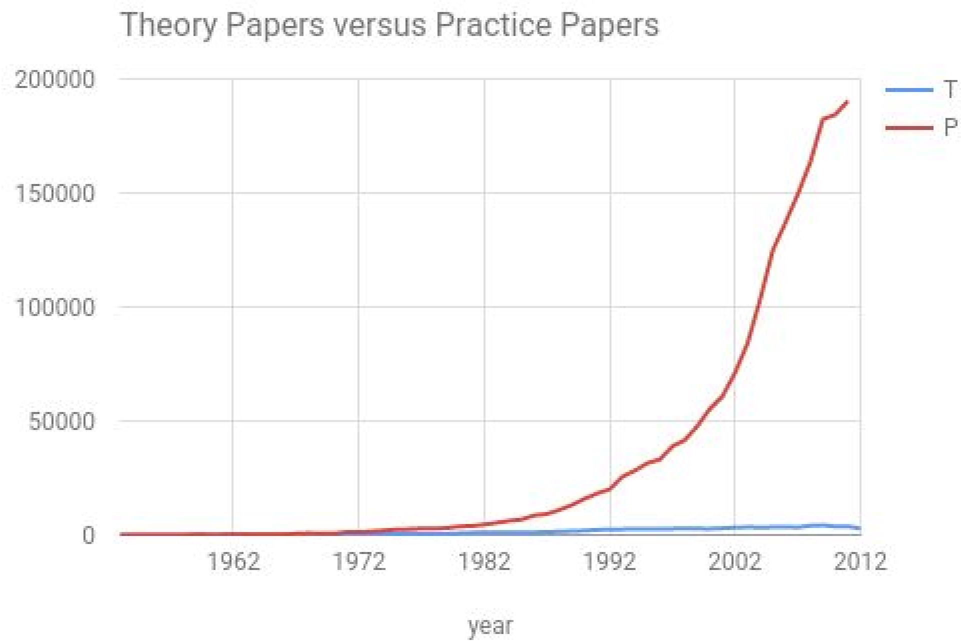
[11] "DBLP - Wikipedia, the free encyclopedia." 2011. 20 Oct. 2015 <https://en.wikipedia.org/wiki/DBLP>

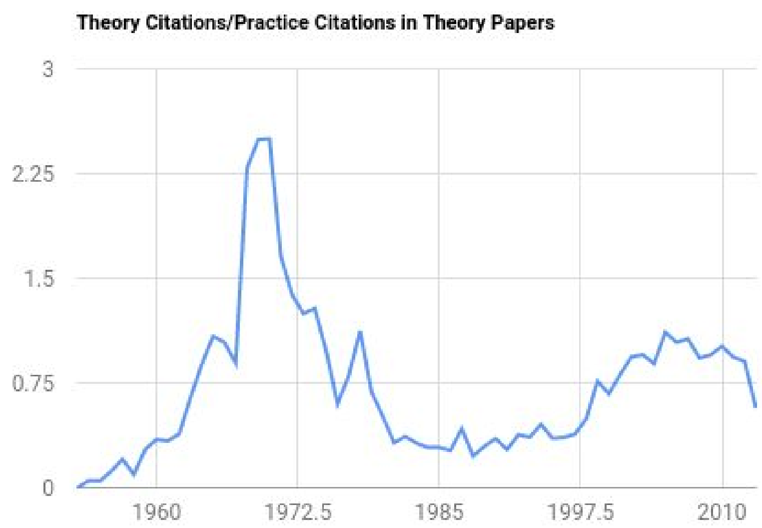
[12] "Association for Computing Machinery - Wikipedia, the free ..." 2011. 20 Oct. 2015 <https://en.wikipedia.org/wiki/Association_for_Computing_Machinery>

[13] Tang, J. "ArnetMiner: Extraction and Mining of Academic Social ..." 2008. <http://dl.acm.org/ft_gateway.cfm?id=1402008>

[14] Theory papers are defined as those published at these venues: STOC,J. ACM,FOCS,SIAM J. Comput.,SODA,Electronic Colloquium on Computational Complexity (ECCC),Commun. ACM,J. Algorithms,Theor. Comput. Sci.,CRYPTO,IEEE Conference on Computational Complexity,Inf. Process. Lett.,ICALP,SPAA,J. Comb. Theory, Ser. B,Random Struct. Algorithms,Computational Complexity,Inf. Comput.,SIAM J. Discrete Math.,Combinatorica,STACS,Discrete Applied Mathematics,J. Complexity,ESA,Math. Program.,Discrete Mathematics,IEEE Transactions on Information Theory,Handbook of Theoretical Computer Science, Volume A: Algorithms and Complexity (A),IPCO,Structure in Complexity Theory Conference,APPROX-RANDOM,FCT,Combinatorics,Algorithmica,ACM Transactions on Algorithms,J. Comb. Theory, Ser. A,ICALP (1),RANDOM,APPROX,RANDOM-APPROX

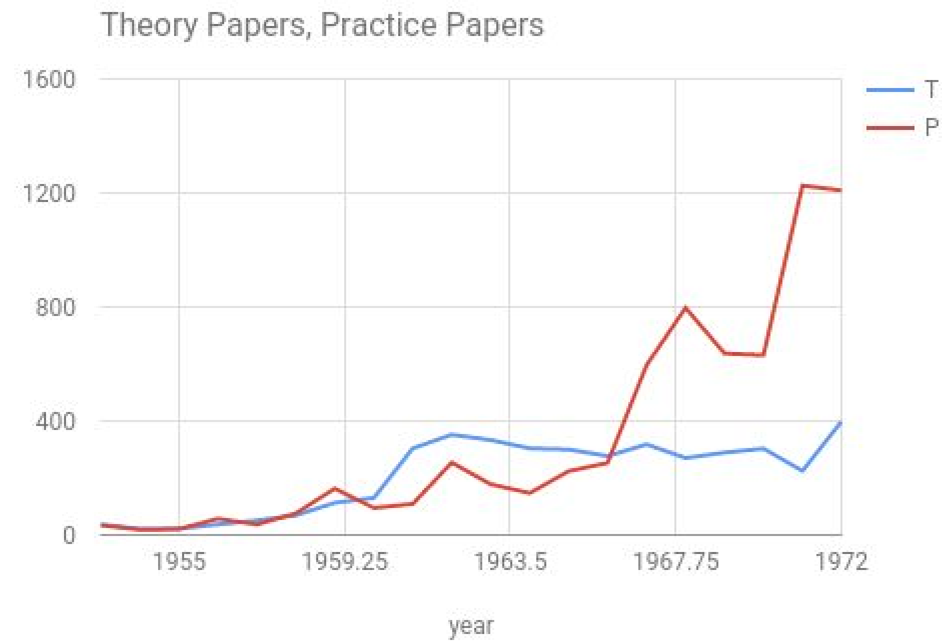


Let us investigate further. We now study citations within theory papers. Specifically, we study the ratio of the number of theory papers they cite versus the number of practice papers they cite.



For the purpose of exposition, the plot has three regions. Pre 1980, between 1980 and 1995, post 1995.

Pre 1980: There is an artifact here. The reason why theory citations outnumber practice ones is because there simply weren't that many practice papers at this point. In fact, the practice papers went to the theory venues. Here is a plot to explain the artifact:



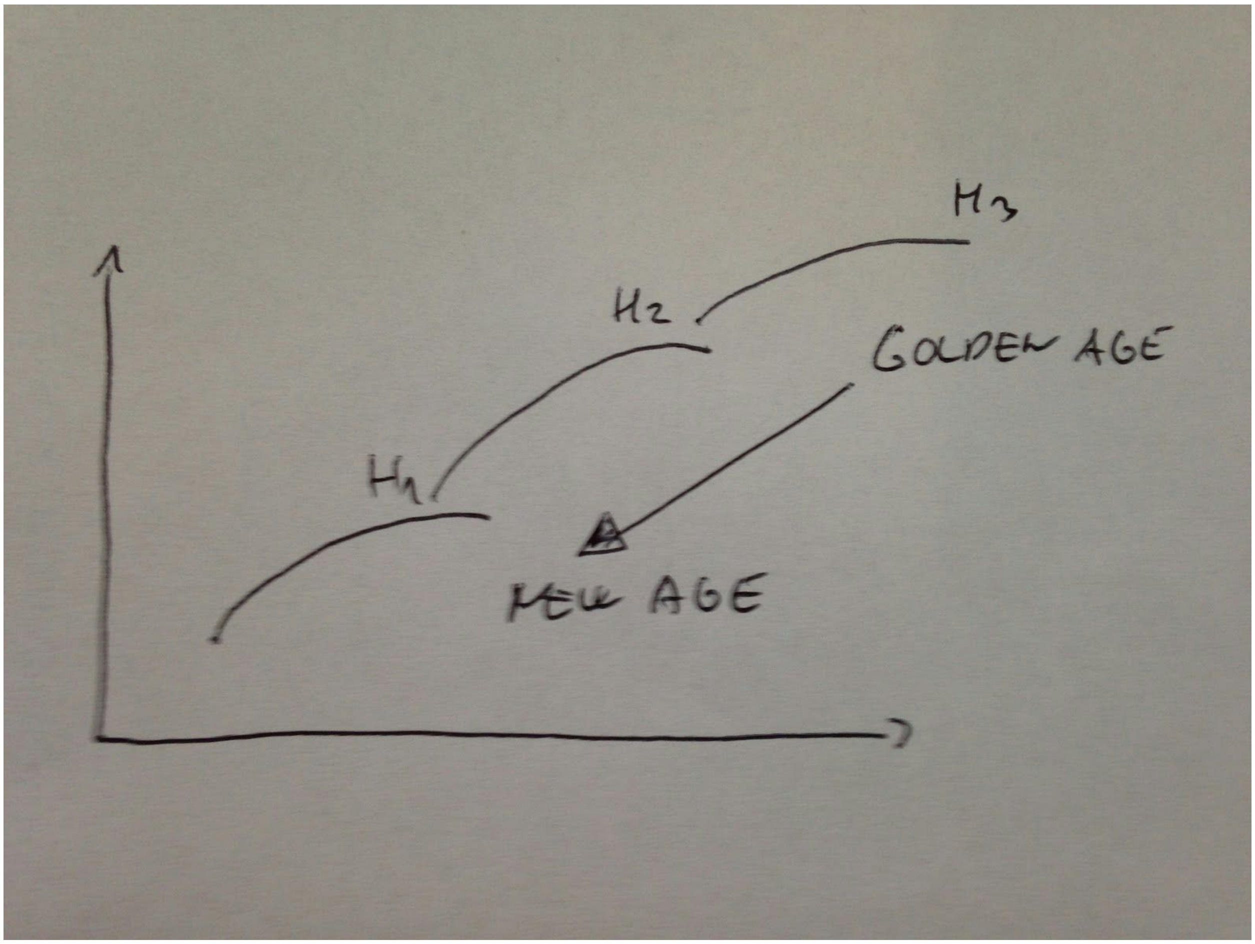
1980 to 1995:
Practice citations outnumber theory citations by a ratio 2:1. Theory papers seem to be seeking inspiration in practice.

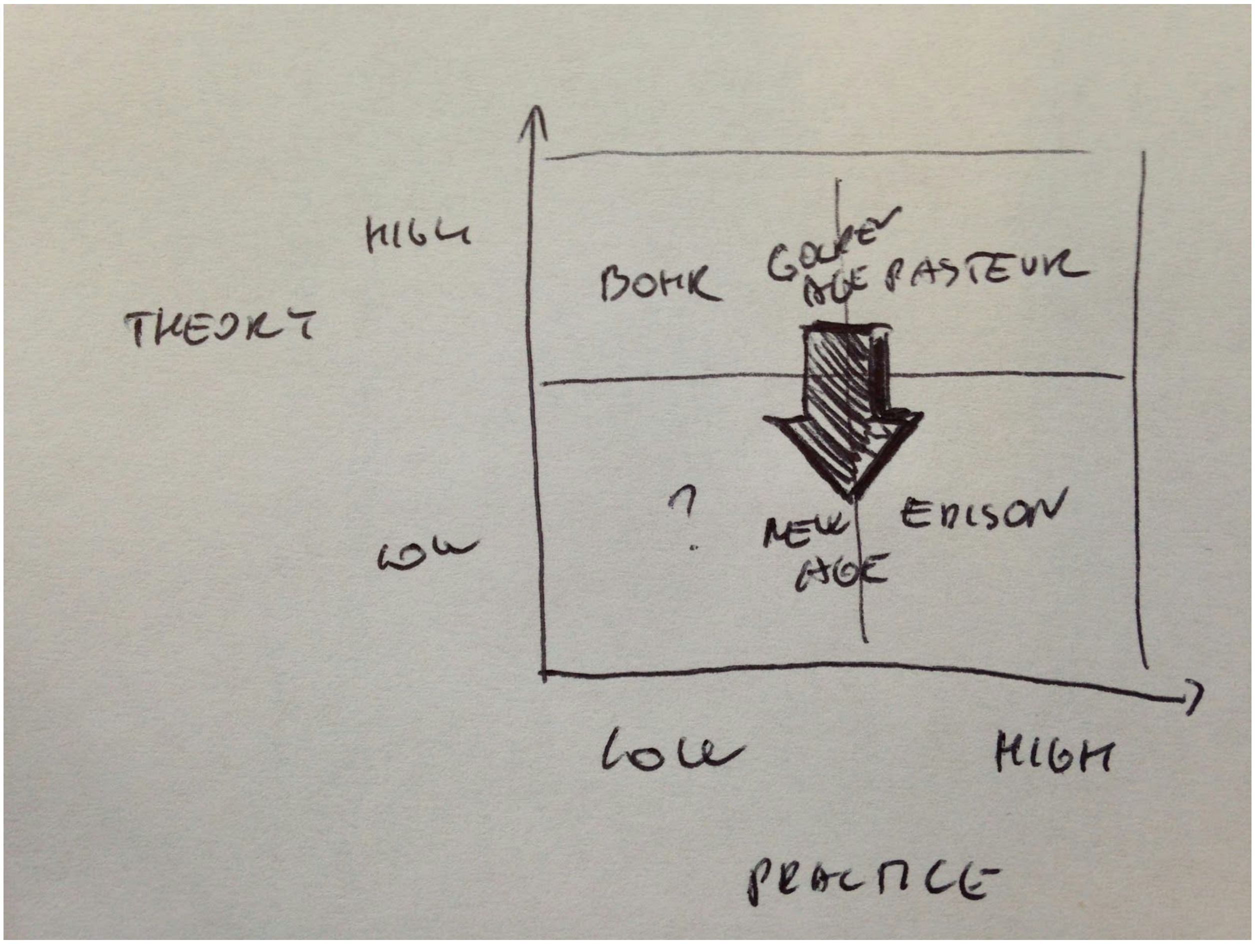
Post 1995:
Practice citations are nearly equal to Theory citations. Influence of practice on theory is reducing. Please see the appendix for details on sampling and analysis of the papers.

The main observation is that a majority of articles from 2014 have little intent of use, and also do not seem as central to the foundations of CS. Articles from 1964 tend to be theoretically simpler but seem obviously practically relevant; modulo one, but that one is squarely in the Bohr Quadrant. Articles from 1984 exemplify a really nice mix of theory and practice.

Conclusion

New age innovations are more H1, they are more aligned to the near term, low risk, strategy of the company, led by financial/operational people at the top with some technology background - there are exceptions. This trend is also supported by the fact that the practice papers cite fewer theory papers (implying that there are fewer innovations that change the industry at its fundamentals to cause revolutionary waves) causing more Edison's and less Pasteurs.





Mark Weiser, Parc's chief technologist. "Young people coming here now are interested in commercial development of their research, which was not true in the past... When I was starting out, Albert Einstein was my hero. To the younger people, Bill Gates is their hero."

[1] Putting Ideas to Work: The Case of Xerox PARC, by John Holusha Published: January 1, 1998

Randy Katz, a professor of computer science at UC Berkeley, argues in the uniformly thoughtful comments on Welsh's post that all industrial research centers are temporary by their very (unprofitable) nature. A wise older colleague, Lotfi Zadeh actually, observed some years ago that "research nirvanas never last forever." In my 35 year career, I have seen the rise (and fall) of Bell Labs, Xerox PARC, and IBM Research that were and are no longer "unfettered research laboratories, unconstrained by the winds of the marketplace." This is not to say that they don't do useful and good work – just that the nature of the [1]

Appendix -- Corporate Research Lab Histories

In this section we summarize the key historical events of a few emblematic research laboratories. The information presented here has been used at various places in the document to highlight real examples supporting our finding of the Golden and New Age models. In this section we present these events per research laboratory.

Bell Labs

Xerox PARC[15][16][17][18]

The predecessor of Xerox Corporation, Haloid Company, was founded in 1906 as a manufacturer of photographic paper. In 1947 company obtained the license to basic xerographic patents. Subsequently the company perfected and marketed the first xerographic copying machines and by 1959, Xerox invented a new industry and launched itself on a decade of spectacular growth. *The Xerox Corporation expanded operations and grew from $176 million in 1963 to $4 billion in sales by 1975. From the mid-1960s to the mid-1970, Xerox revenues grew at an average annual rate of about 23 percent per year and profits increased at an average rate of about 20 percent*[19]. This phenomenal growth and about 95% market share was due to the patents Xerox's owned and which ensured its monopoly position in the market.

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[15] "Xerox PARC -- Innovation without Profit?," IBS Center for Management Research Case Study, BSTR/150

[16] Xerox Corporation: Surviving the Competitive Crisis, Case- study by William R. Boulton, Olan Mills Professor of Strategic Management, Auburn University, 1996

[17] Xerox: The Downfall http://www.businessweek.com/2001/01_10/b3722001.htm

[18] Putting Ideas to Work: The Case of Xerox PARC, by John Holusha Published: January 1, 1998

[19] Xerox Corporation: Surviving the Competitive Crisis, Case- study by William R. Boulton, Olan Mills Professor of Strategic Management, Auburn University, 1996

It was during this favorable times in 1970, when the business was booming and money was not an issue for Xerox, when the Palo Alto Research Center (PARC) was established. PARC was setup to work on the future of technology and in particular the future of computers. The Palo Alto location for the research center was selected consciously to be away (3000 miles) of the corporate headquarters in Rochester NY. The motivation was to avoid that the research scope is pulled back to the traditional research activities Xerox was running close to it core business. The scope and location of the center contributed to the fact that PARC was detached from the corporate headquarters and agenda and operated as a centralised research facility isolated in it own Ivory tower. PARC was generously funded to make the facility truly world-class. In fact, top individuals were recruited and were promised unlimited funds and freedom to pursue research in the field of their interest. At that time the Bay Area was not yet know as the Silicon Valley, which well illustrate that there was plenty of new discoveries to be done in the computer science space that PARC targeted. For Xerox as well as for the whole industry the computer and digital technology research that PARC was chartered for was clearly Horizon 3 research.

It is well documented that many invention of PARC were commercialized by other companies and PARC had limited if any revenue from these technologies. For example Robert Metcalfe, who invented Ethernet at PARC between 1973 and 1974, left the research center in 1979 to form 3Com. By the end of the 1980s, Ethernet was clearly the dominant network technology, and 3Com became a major company. A famous quote from Metcalf well captures the situation: "I don't have this house because I invented Ethernet, I have this house because I sold Ethernet for a decade." Another often cited example is that of the GUI. Although PARC had a very advanced solution Xerox did not see the potential in the technology. At the same time Steve Jobs, who was approaching the personal computer from a business perspective saw the value and incorporated GUI technology in the Macintosh. This latter example also highlight the need of business lens to make sure the business value of a technology is captured. Many other key computer scientist left PARC to pursue commercialization of their inventions and became early employees of other emblematic companies like Microsoft and Adobe Systems.

While the above failures are the most cited, it must be noted that PARC innovations that were inline or adjacent to the core business like in the laser printer and various material science related discoveries were successfully commercialized by Xerox. That is Xerox was more successful to commercialize Horizon 1 and 2 research activities.

Xerox’s copier patents expired over the 1970s and 1980s and as a result Xerox lost its monopoly on the market and in the 1980s the company faced fierce competition. Although competition intensified during the subsequent years, the result on Xerox’s bottom line was not shocking. *Between the mid-1970s and 1980, revenue and profit growth slipped to an average annual rate of about 16 and 14* *percent, respectively*[20]. The competition for low-end office copying segment came from Japan: Canon, Ricoh and Sharp, while the middle and high-end was attached by US competitors: IBM and Kodak. By the mid 1980s the drop of market share and profitability reach a level that Xerox had to react. Xerox worked to establish competitive benchmarks to understand how it competitors managed to deliver comparative products at lower costs. The focus of the effort was to improve operations and as result Xerox introduced a “leadership through quality” program. This program included a realignment of the company to deliver products that fulfilled customer requirements. The program managed to stop Xerox decline and even turned around the company a little bit. During this period Xerox headquarters was focused on the core business and to improve operations. To this end, the focus was clear Xerox is a copier and not a computer company. All the same time PARC came up with the great new ideas about computer industry, but there was no interest and bandwidth in the headquarters to deal with it. It is important to note that research results from PARC that were inline with the corporate strategy like laser printer technology and various material science results have been adopted and commercialized by Xerox. This highlights that the key issue was with Horizon 3 innovation and the lack of its handling built into the corporate strategy as well as lack from the CEO to support commercialization of completely new businesses. Interestingly diversification was on Xerox's agenda, however, instead of the computer industry in which they had key competence and IP, they ventured into the financial services business. Financial services and insurance, contributed about a quarter of Xerox's revenues by the mid 1980s.

The next step was that at the end of the 1980s Xerox gave top priority to product development and as a result in 1988 and 1989 Xerox introduced more new copiers and laser printers than during any five-year period in its history. With the development of the digital photocopiers in the 1990s Xeroxs managed to get ahead of the competition.

Around 2000 the company reported record loss due to pure market conditions and internal top management crises which was followed by replacement of the CEO. The crisis was so severe that even the humiliation of Chapter 11 bankruptcy was not completely out of question. *Xerox posted a loss of $198 million over the last three months of 2000, the largest quarterly loss in a decade. With $2.6 billion in debt coming due this year and a $7 billion bank loan looming in 2002, Xerox is cutting spending, firing workers, and trying to raise as much as $4 billion by selling off assets.*[21] This subsequent restructuring and cost saving program determined the faith of PARC, and the decision to separate the research center for Xerox, making it responsible to rais funding for its research endeavours. This revenue and profitability mandate forced PARC to move to more shorter term research activities and partner early own with organizations that need the research services PARC

[20]Xerox Corporation: Surviving the Competitive Crisis, Case- study by William R. Boulton, Olan Mills Professor of Strategic Management, Auburn University, 1996
[21] Xerox: The Downfall http://www.businessweek.com/2001/01_10/b3722001.htm

provides and competence it possesses. This inherently means that PARC is doing research for companies who have the particular technology on their radar and like fall within Horizon 1 or 2 innovation category.

PARC has developed a lot of groundbreaking technologies in the 1970s and 1980s, including Ethernet, GUI, the mouse, however Xerox failed to bring these technologies to market. This is explained by the very narrow business focus of the mother company. While PARC interpreted its research agenda being a Horizon 3 exploration of the office of the future, Xerox was only looking one step ahead for the next copier machine, essentially a Horizon 1 and maybe 2 innovation expectation.

In 2002 PARC was separated from the parent company as a wholly owned subsidiary of Xerox. PARC's new agenda was to provide research services and innovation products to other corporations and cover a broad field and industries. In essence, PARC turned into a profit oriented research laboratory, that has to earn its own revenues and sell its advanced research capabilities and competence as a service and license its Intellectual Property to sustain its existence. Xerox is only one customer of PARC. Today, Xerox has five research centers, including PARC. However, the other four are integral part of the mother company and their focus is much more limited and close to the core business and products of Xeroxs.

When PARC became a for-profit subsidiary of Xerox it started to practice what we call today open innovation. PARC knew how to engage a design firm, license IP, and form joint ventures, but there was no experience of how to truly co-develop innovations with external partners. PARC was the true champion of this type of research and partnerships.

Innovation in Xerox today is multifaceted covering a broad range of businesses. However the core of research is still centered around printing and expanded to provide business outsourcing and related services. *Our research agenda spans our traditional printing and imaging domains and extends into technology based solutions and business process outsourcing and services.*[22]

[22] http://www.xerox.com/downloads/usa/en/innovation/innovation_xig_brochure.pdf

Microsoft Research

Founded on April 4, 1975 by Paul Allen and Bill Gates, Microsoft Corporation has become one of the world's most valuable companies. It dominated the personal computer operating system market with MS-DOS in the mid 1980's.[23]

Starting from MS-DOS in 1980, to Windows 1.0 (1982-85), to Windows 98 (1998 - 2000), to Windows 10 (2015), Microsoft has kept innovating on their flagship product, the Windows Operating System, which revolutionized the software world.[24] Year over year, the graphical user interface, the applications, the functionalities were improved or added. Technological capabilities increased with improved hardware and cost decreased with better manufacturing processes in the PC business, leading to increasing sales. This (among other factors) fueled the innovation. Microsoft also invested in some new markets and new technologies that we consider as Horizon 1 or Horizon 2.

Microsoft Research's Silicon Valley outpost, located in Mountain View, Calif., was founded in 2001. The MSR Silicon Valley lab was primarily focused on distributed computing research, including "privacy, security, protocols, fault-tolerance, large-scale systems, concurrency, computer architecture, Internet search and services, and related theory," according to the web page for the lab.[25] This center was shut down in September 2014, however the research continued in other locations. Microsoft operates a number of Microsoft Research labs worldwide, including labs in Asia, Cairo, Cambridge (UK), Europe, India, Israel New England, New York City and Redmond. Microsoft did not back down on research in the silicon valley. They still have 2500 employees that work on Skype, Yammer, Bing, Outlook.com and Xbox.[26]

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[23] https://en.wikipedia.org/wiki/Microsoft
[24] http://windows.microsoft.com/en-us/windows/history#T1=era1
[25] http://research.microsoft.com/en-us/labs/siliconvalley/
[26] zdnet.com/article/microsoft-to-close-microsoft-research-lab-in-silicon-valley

During the course of this time, most of the notable innovations in the were in horizon 1 and 2: new/upgrade technology for the same markets - except for some new starts. For example, Microsoft came out with the popular gaming console Xbox's first release in 2001. Being a software based company, and building a hardware for a completely different market was a horizon 3 innovation. However it was followed by upgraded models (Xbox 360 in 2005, Kinect, Xbox One in 2013). Kinect changed how people played games. Microsoft already had a Windows Live Messenger and Lync services for corporate usage. These messenger services were free and they did not incorporate connectivity to telephone lines. Microsoft acquired Skype (one method of innovation) in 2011 to add these capabilities and expand more on the communications capability.[27]

Cloud and IoT are very new fields for ICT. For the hardware vendors, it is a new era for creating innovative devices. For the software companies, it opens up opportunities for new OS platforms, computing platforms, computing services and applications for users. Today, in ICT domain, a significant amount of research effort is put into building services and applications for cloud based computing and services. Over a period of time, Microsoft has innovated on its software products, built for home, small business and enterprises, to run on servers for corporates. These have now moved to cloud with significant innovation to match different set of requirements. Microsoft's Azure provides a cloud computing platform and services. Services like Azure Machine Learning - "cloud based tool to provide users to develop machine learning models" - are now being developed and made available.[28] Microsoft researchers have created a scarf that can be commanded to heat up and vibrate via a smartphone app, part of an exploration of how the accessory could eventually work with emerging biometric- and emotion-sensing devices.[29] These trends show that there is a lot of innovation in different fields and areas from where the company started. Over this period of time, there are fewer and fewer moon shots. However, will the company still stay a software company?

Apple

We Interviewed an established innovator, an ex-employee of Apple, Jack. We have changed names here for discretion. Apple started working on building the iPhone in 2004[30]. Many SW technologies

[27] http://www.wired.com/2011/05/microsoft-buys-skype-2/
[28] http://blogs.microsoft.com/next/2015/07/10/the-next-evolution-of-machine-learning-machine-teaching/
[29] http://www.technologyreview.com/news/534261/microsoft-researchers-get-wrapped-up-in-smart-scarf/
[30] https://en.wikipedia.org/wiki/IPhone

were evaluated for adding onto the iPhone as a feature. At the time, the technology X, that Jack had pioneered at his previous company, was not yet mature. Steve Jobs did not think the technology X would ever be useful and so rejected the idea of having it integrated in the iPhone's software at that time. In 2007, technology X had matured to an extent and was released to the market - spun off as a part of a company from the parent. In 2010, technology X was exposed to Steve Jobs by accident during his review of various technologies for Apple's next generation products. Technology X was selected for iPhone in two days of review and eventually led to Apple acquiring the company. Steve Jobs had the vision and an attitude to realize the vision no matter what. It took innovation at different levels (horizons). This acquisition was one of such examples. During the integration phase, Jack had regular meetings with some of the top executives at Apple to review the innovative features that were needed for technology X to be effective on the iOS platform for end users. Over a course of 3 months, the same features were presented to the executives. The executives did not comprehend the significance of the features and they gave inconsistent feedback, while delaying the development, and hence, delaying the release of technology X that was bought for deploying in the field. Jack notes that he pointed it out during 1:1 with the executives and found that there was no risk taking behavior for innovation, as that seen with Jobs. Eventually technology X made it to the market in iPhones. Jack does not deny that the executives had expertise in certain fields but he feels that they perhaps lacked the guts, which he knows is necessary for innovation, to go out boldly with what they believed in. Jack had similar experiences at different times with the top executives as and notes that their non-innovative behavior was one of the reasons why none of these executives were selected to be the next CEO at Apple. The top executives knew that Jobs' position would need to be replaced and hence they wanted to prove that they were capable. However they could not deliver innovation beyond Jobs' vision. Overall PEST analysis shows that Apple would rate high on E/S, but low on P/T, per Jack's perspective.

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History:

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[2]
http://blogs.berkeley.edu/2013/01/14/the-endless-frontier-u-s-science-and-national-industrial-policy-part-1/
[3] Donald E. Stokes, Pasteur's Quadrant – Basic Science and Technological Innovation, Brookings Institution Press, 1997.

[4] Carlota Perez – Technological revolutions and techno-economic paradigms; 2009. "Technological revolutions and techno-economic paradigms", Cambridge Journal of Economics, Vol. 34, No.1, pp. 185-202
[5] Michael E. Porter and James E. Heppelmann: “How Smart, Connected Products Are Transforming Competition,” HBR, November 2014.
[6] https://en.wikipedia.org/wiki/Bell_Labs
[7] https://en.wikipedia.org/wiki/PARC_(company)
[8] Christopher Mims: “Is the Death of Intel Research a Harbinger of Doom for Privately Funded Technology Research?,” MIT Technology Review, April 4, 2011
[9] Ikhlaq Sidhu: “A Model for Global Engineering Leadership,” Fung Institute for Engineering Leadership, 2015
[10]

Studying the relation between theory and practice

Computer science is clearly practically relevant field; arguably, no field has had a similar magnitude of impact on society in the past 50 years via the development of computers, the Internet, and information technology. It is also a mathematical field. Indeed the conception of the modern computer has its origin in a question central to mathematics about what can be proved/disproved automatically, a question studied by Turing and Godel[31].

We now study the evolution of CS research over time in the framework of the four quadrant model[32]. Aspirationally, we would like research to both further understanding, but also be practically relevant, i.e., fall in the Pasteur quadrant. We are going to perform two analyses.
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Analyzing CS papers, citations over time

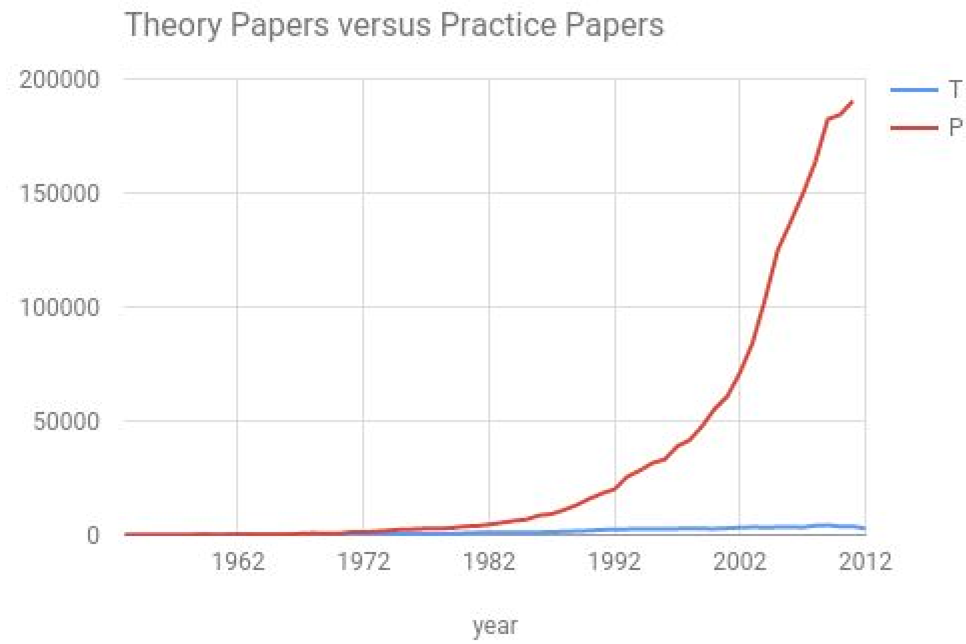
[31] "The Modern History of Computing (Stanford Encyclopedia of ..." 20 Oct. 2015 <http://plato.stanford.edu/entries/computing-history/>
[32] "Pasteur's quadrant - Wikipedia, the free encyclopedia." 2012. 20 Oct. 2015 <https://en.wikipedia.org/wiki/Pasteur's_quadrant>

For this analysis, we use data from DBLP[33] and ACM[34], curated by Tang et al.[35]. This dataset contains the list of all CS papers with information about year of publication, the conference of publication and citations.

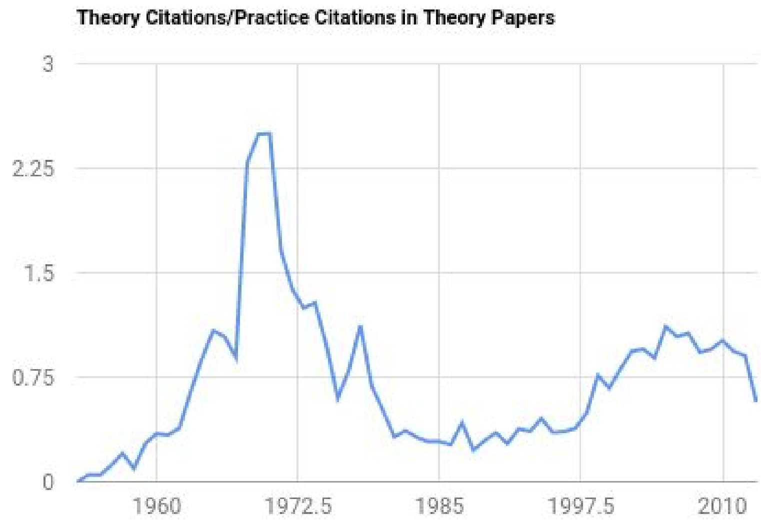
We classify papers as theory papers if they appear in a specific list of conferences[36]. This list has been sanity checked for precision by three researchers in the area of CS theory, for recall by examining citation patterns across these papers.

Our first observation is simple: Namely that over time, the fraction theory papers have fallen. There are two possible interpretations. That theory plays an increasingly smaller role in the grand scheme of things. Or that this graph simply represents the increasing practical relevance of CS.

[33] "DBLP - Wikipedia, the free encyclopedia." 2011. 20 Oct. 2015 <https://en.wikipedia.org/wiki/DBLP>
[34] "Association for Computing Machinery - Wikipedia, the free ..." 2011. 20 Oct. 2015 <https://en.wikipedia.org/wiki/Association_for_Computing_Machinery>
[35] Tang, J. "ArnetMiner: Extraction and Mining of Academic Social ..." 2008. <http://dl.acm.org/ft_gateway.cfm?id=1402008>
[36] Theory papers are defined as those published at these venues:
STOC,J. ACM,FOCS,SIAM J. Comput.,SODA,Electronic Colloquium on Computational Complexity (ECCC),Commun. ACM,J. Algorithms,Theor. Comput. Sci.,CRYPTO,IEEE Conference on Computational Complexity,Inf. Process. Lett.,ICALP,SPAA,J. Comb. Theory, Ser. B,Random Struct. Algorithms,Computational Complexity,Inf. Comput.,SIAM J. Discrete Math.,Combinatorica,STACS,Discrete Applied Mathematics,J. Complexity,ESA,Math. Program.,Discrete Mathematics,IEEE Transactions on Information Theory,Handbook of Theoretical Computer Science, Volume A: Algorithms and Complexity (A),IPCO,Structure in Complexity Theory Conference,APPROX-RANDOM,FCT,Combinatorics,Algorithmica,ACM Transactions on Algorithms,J. Comb. Theory, Ser. A,ICALP (1),RANDOM,APPROX,RANDOM-APPROX

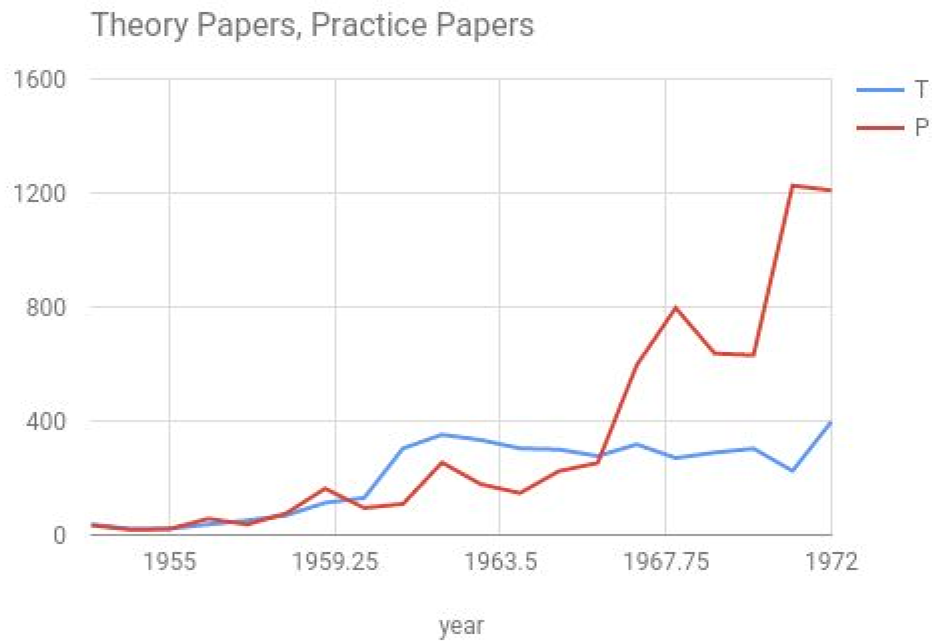


Let us investigate further. We now study citations within theory papers. Specifically, we study the ratio of the number of theory papers they cite versus the number of practice papers they cite.



For the purpose of exposition, the plot has three regions. Pre 1980, between 1980 and 1995, post 1995.

Pre 1980: There is an artifact here. The reason why theory citations outnumber practice ones is because there simply weren't that many practice papers at this point. In fact, the practice papers went to the theory venues. Here is a plot to explain the artifact:



1980 to 1995:
Practice citations outnumber theory citations by a ratio 2:1. Theory papers seem to be seeking inspiration in practice.

Post 1995:
Practice citations are nearly equal to Theory citations. Influence of practice on theory is reducing.

Next, we do a different analysis to see if this observation that theory and practice are diverging holds.

A Stratified-Sampling Analysis of a sample of Journal of ACM articles from 1964, 1984, and 2014.

The purpose of this section is to complement the data-driven analysis in the previous section using an in-depth, manual investigation. The idea is to stratify time into three slices, sample theory papers from each slice and check how practically relevant they are. This is a riff on Donald Knuth's analysis where he studied Chapter 3 verse 16 from various Bible texts.[37]

We will sample papers from the Journal of ACM is the premier computer science journal on theoretical topics. The articles from this journal are a good representation of the frontier of mathematical issues in CS at a that point in time.

Our analysis will focus on the two axes of the two axes of the Pasteur Quadrant, i.e., Quest for Fundamental Understanding and Intent of Use.

1964

Title	Quest for Fundamental Understanding	Intent of Use	Notes
Universality of tag systems with P = 2. [38]	Strong, very central to CS	No	Identifies a minimal Universal Turing Machine, has influence on the theory of computational hardness.
Input data source limitations for real-time operation of digital computers[39]	Yes, but relatively simple	Definitely	A simple, information theoretic model of computer memory.
An approach to multilevel Boolean minimization[40]	Yes	Some	Finding minimal boolean presentations of a certain depth.

[37] "3:16 Bible Texts Illuminated: Donald E. Knuth ... - Amazon.com." 2006. 20 Oct. 2015 <http://www.amazon.com/3-16-Bible-Texts-Illuminated/dp/0895792524>
[38] Cooke, J. "Universality of TAG Systems with P-2." 1963. <http://dspace.mit.edu/handle/1721.1/6107>
[39] Schroeder, R. "Input Data Source Limitations for Real-Time Operation of Digital Computers." *Journal of the ACM (JACM)* 11.2 (1964): 152-158.
[40] Lawler, EL. "An Approach to Multilevel Boolean Minimization." 1964. <http://dl.acm.org/citation.cfm?id=321232>

Some analytical procedures for computers and their applications to a class of multidimensional integrals[41]	yes	yes	Algorithms to evaluate integrals analytically.

1984

Title	Quest for Fundamental Understanding	Intent of Use	Notes
Some Hamilton paths and a minimal change algorithm[42]	Yes, but not as central as the first of the 1964 papers	minimal	Algorithms for a restricted case of hamiltonian paths
Serializability by locking[43]	Yes	Yes	locking primitives for database systems
An end-to-end approach to the resequencing problem. [44]	Medium	Yes	studies the delay introduced by resequencing packets.
A proof procedure for data dependencies.[45]	Yes	Yes	proof procedure to check if a database is consistent/semanticall y meaningful.

[41] Hartt, K. "Some Analytical Procedures for Computers and Their ..." 1964. <http://dl.acm.org/citation.cfm?id=321242>
[42] Hartt, K. "Some Analytical Procedures for Computers and Their ..." 1964. <http://dl.acm.org/citation.cfm?id=321242>
[43] Yannakakis, M. "Serializability by Locking - ACM Digital Library." 1984. <http://dl.acm.org/citation.cfm?id=322425>
[44] Baccelli, F. "An End-to-End Approach to the Resequencing Problem." 1984. <http://dl.acm.org/citation.cfm?id=1883>
[45] Beeri, C. "A Proof Procedure for Data Dependencies." 1984. <http://dl.acm.org/citation.cfm?id=1636>

2014

Title	Quest for Fundamental Understanding	Intent of Use	Notes
Constraint Satisfaction Problems Solvable by Local Consistency Methods.[46]	Medium	Yes	Local methods to tackle constraint satisfaction
Nearly Optimal Solutions for the Chow Parameters Problem and Low-Weight Approximation of Halfspaces.[47]	Yes, but does not seem central to CS	Weak	Improves algorithms for a somewhat obscure electrical engg problem.
Computing All Maps into a Sphere. [48]	Barely a CS problem	No	
An Additive Combinatorics Approach Relating Rank to Communication Complexity[49]	Yes, not very central	No	Relation between rank of a 0/1 matrix, and its communication complexity.
Fault-tolerant algorithms for tick-generation in	Medium	Strong	

[46] Barto, L. "Constraint Satisfaction Problems Solvable by Local ..." 2014. <http://dl.acm.org/citation.cfm?id=2556646>
[47] De, A. "Nearly optimal solutions for the chow parameters problem ..." 2012. <http://dl.acm.org/citation.cfm?id=2214043>
[48] Čadek, M. "Computing all maps into a sphere - ACM Digital Library." 2012. <http://dl.acm.org/citation.cfm?id=2095117>
[49] Ben-Sasson, E. "An additive combinatorics approach relating rank to ..." 2012. <http://eccc.hpi-web.de/report/2011/157/revision/1/download/>

asynchronous logic: Robust pulse generation.[50]			
Fast Interactive Coding against Adversarial Noise[51]	Yes	Most likely not, because the noise model does not seem practical	

The main observation is that a majority of articles from 2014 have little intent of use, and also do not seem as central to the foundations of CS. Articles from 1964 tend to be theoretically simpler but seem obviously practically relevant; modulo one, but that one is squarely in the Bohr Quadrant. Articles from 1984 exemplify a really nice mix of theory and practice.

[50] Dolev, D. "Fault-tolerant algorithms for tick-generation in asynchronous ..." 2014. <http://dl.acm.org/citation.cfm?id=2560561>
[51] Brakerski, Z. "Fast Interactive Coding against Adversarial Noise - ACM ..." 2014. <http://dl.acm.org/citation.cfm?id=2661628>

Figure: Strokes: Quadrant model of research

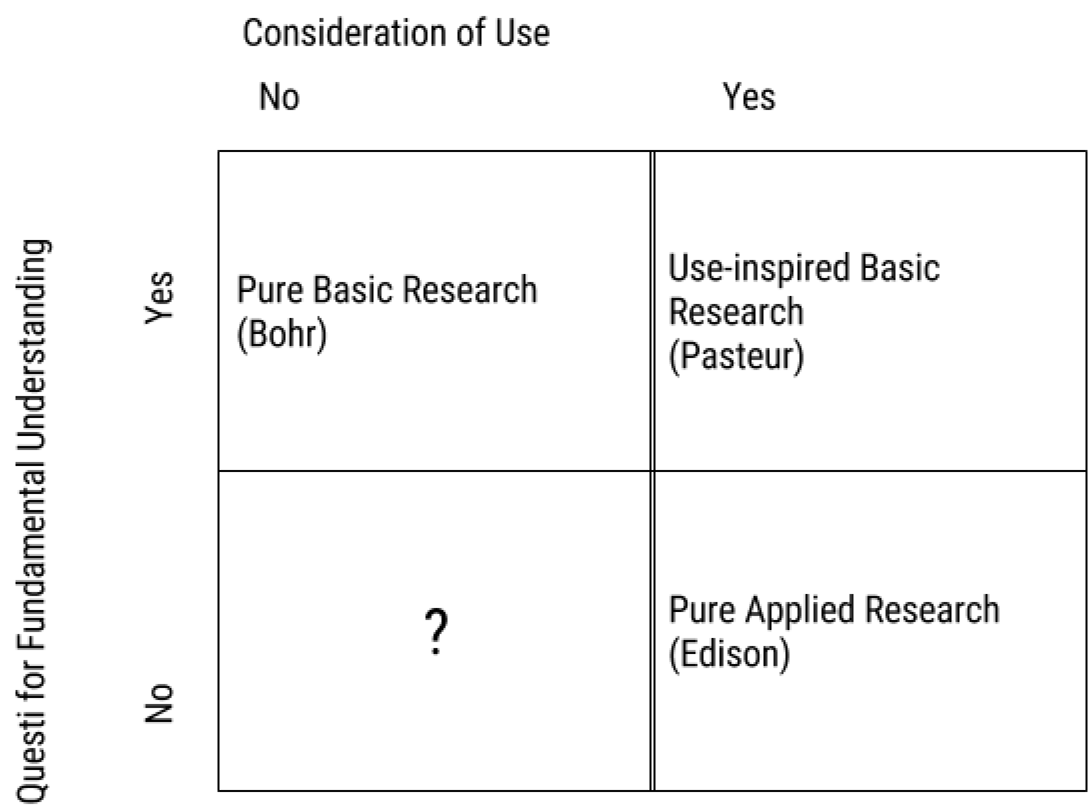
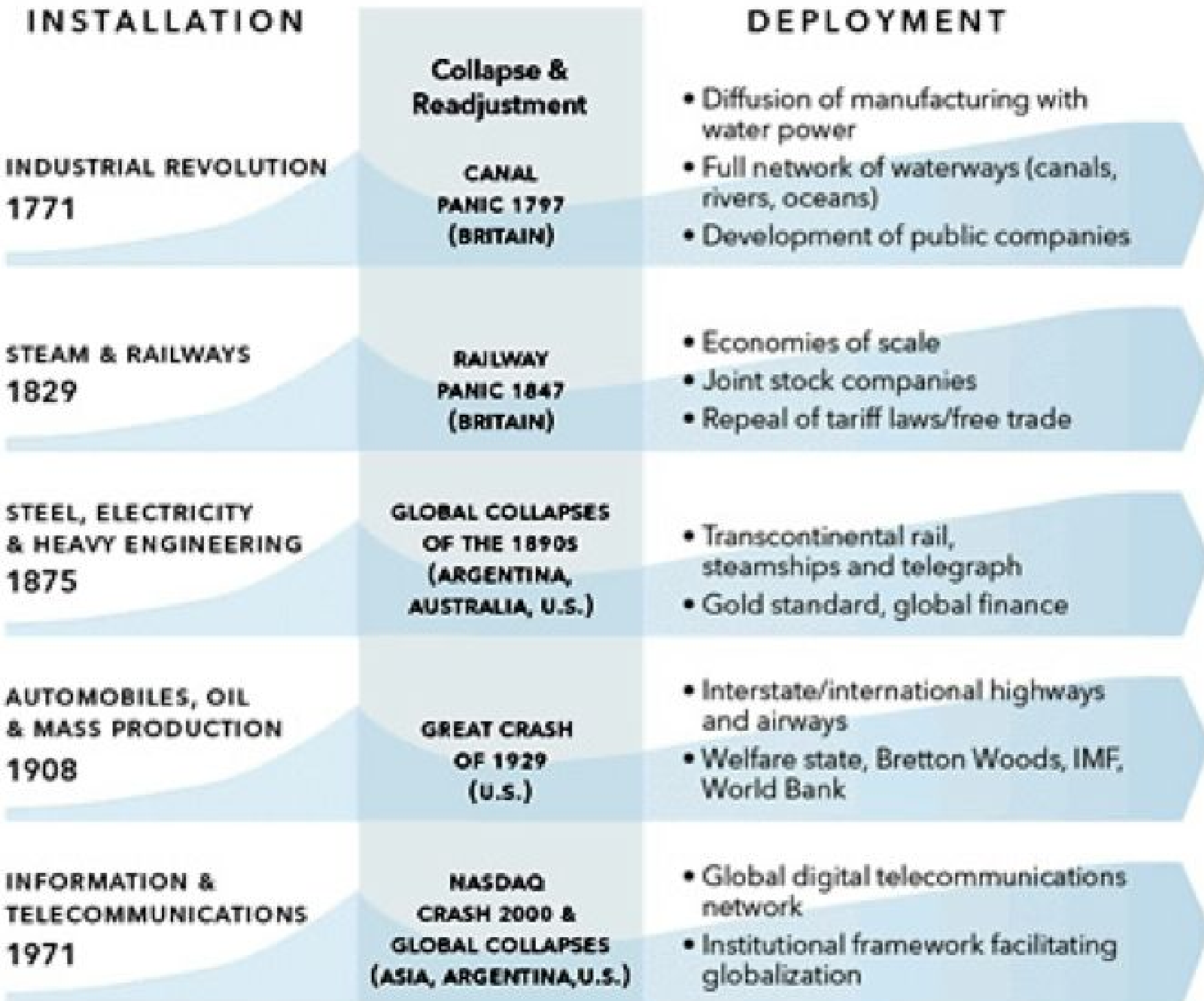
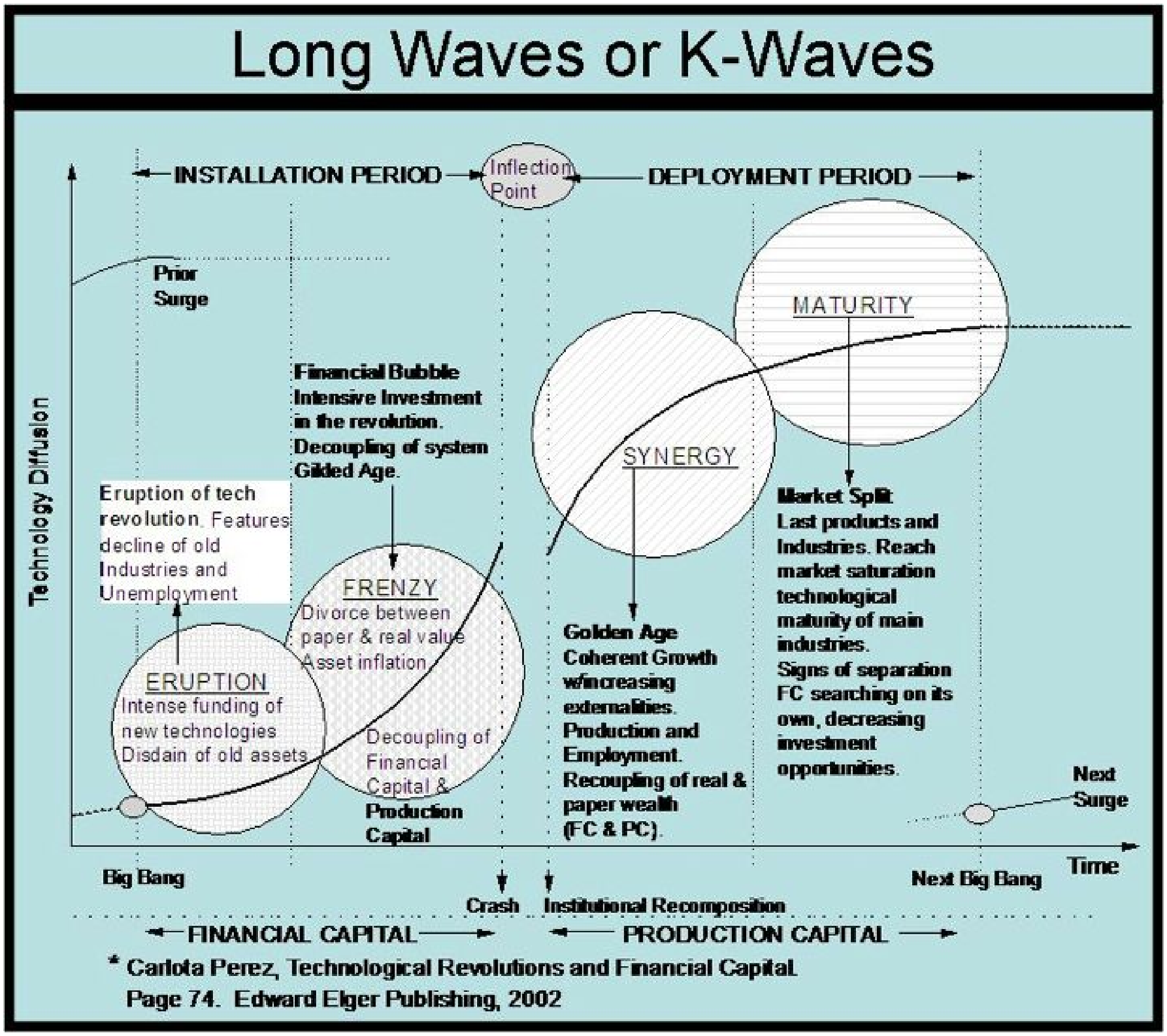


Figure: Carlota Perez:





Notes about Prof. Sidhu's paper about R&D models:[52]

This paper examines 6 models (roadmap, pivot, need based, integrated, m&a, corporate) for R&D within successful companies. It studies how projects are defined, funded, and measured. The methodology used is to survey past or current employees of the companies studied.

[52] Sidhu, Ikhlaq, Tal Lavian, and Victoria Howell. "R&D Models for Advanced Development & Corporate Research."