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Hidden in Plain Sight: QWERTY, the Search for Optimality and IP Complementarity (2nd Revision)

Abstract

The evolution of the QWERTY keyboard layout has been the subject of much debate. Prior discussions of QWERTY, however, have largely focused on engineering issues, and ignored the key competitive and intellectual property strategies surrounding the design. We argue that the keyboard layout QWERTY was a consequence of entrepreneurial mindfulness, creative design and part of a highly efficient strategy rather than an accident of history. Unlike past discussions of the QWERTY innovation, this paper also shows how complementarities in intellectual property rights protection played an integral role in the early development of QWERTY and helped to effectively conceal the source of the efficiency advantages that QWERTY helped deliver at the time. Finally, we suggest possible arguments why the QWERTY standard has continued into the modern age separate from a path dependence argument. This further serves to raise serious questions over QWERTY's forced servitude as 'paradigm case' of inferior standard in the path dependence literature.

Keywords: QWERTY, path dependence, optimality, trade secret, IP complementarities

Introduction

Path dependence, in its most basic form, can be described as a, "dynamic process of a variable y with an equilibrium distribution that is a function of initial conditions, y0, and possibly an early sequence of outcomes y1, y2, y3, . . . , y's in reaching that equilibrium" (Jackson and Kollman, 2012, p. 157). Over time the notion of path dependence has been applied to various institutional, political, and economic phenomena, such as the growth of bureaucracy, the inability of organizations to adapt strategically to changing market conditions, the nature of regional economic development, the lack of democratic political reforms in Africa, and the absence of public health care in the United States (e.g., Brekke, 2015; Jackson and Kollman, 2010; Jackson and Kollman, 2012; Koch, 2011; Maielli, 2015, Maielli, 2017; Mahoney and Schensul, 2009; Puffert, 2024). It has been noted, however, that not all phenomena that appear influenced by history, or stuck in time, are examples of true path dependent equilibrium. Instead, many such phenomena are actually equilibrium independent with slow rates of innovation, something that often makes the empirical identification of path dependent equilibrium difficult. Three conditions are often used to define true path dependence from an empirical point of view. First, there is a theoretical reason for the initial state lasting for an extended period of time, second, after a very long historical period, the initial conditions still exist or matter within the system, and third, there appears to be an equilibrium established over time based on endogenous variables related to the design (Jackson and Kollman, 2012).

Path dependence was first discussed in detail with respect to technological systems, such as the QWERTY keyboard arrangement, by W. Brian Arthur in the early 1980s (Arthur, 1983). Arthur then followed up his work on path dependence and behavioral lock-in technology standards with additional examples, such as the VHS versus Beta video cassette format battle. Paul David added further discussion of the QWERTY keyboard design in his 1985 *American Economic Review* article, which solidified two important misconceptions in the minds of many. First, that the QWERTY keyboard format, introduced by inventor Christopher Latham Sholes, was less efficient than other possible keyboard designs, such as the 1936 Dvorak and Dealy keyboard (now referred to as the Dvorak Simplified Keyboard, or DSK). It is David's argument that the QWERTY inefficiency was perhaps known very early in the development of the typewriter, since other keyboard arrangements were offered soon after the QWERTY typewriter design. Second, David uses the longevity of the QWERTY keyboard design to highlight the now widely accepted notion of path dependence, where an inferior technology or solution becomes 'locked in' over time due to various economic conditions such as the cost of conversion and the quasi-irreversibility of investments (David, 1985, p. 336). David, then extends the QWERTY path-dependence argument to other systems, pointing out the danger of standardizing around wrong systems.

The notion of path dependence and locked-in design is now almost taken for granted in many economic circles and business innovation textbooks, with the underlying assumption that letting the competitive market establish standards may actually be inefficient in the long-term, and that early 'random events' can ultimately lead to an inferior system being adopted. David's analysis of path dependence has led to QWERTY now being widely cited as the classic paradigm case of path dependence where an inferior standard is adopted as a consequence of 'accidents of history', and this standard has continued over time, in spite of superior designs (Puffert, 2024).

While supporters of the path dependence argument, such as David (1985; 2001) and Arthur (1983, 1989) appear to argue for a strict interpretation of path dependence, where seemingly random 'accidents of history' provide the foundational technology standard that becomes 'locked-in' over time, and "unable to shake free of their history" (David, 2001, p. 19), other authors take a more behavioral, or 'mindful deviation' perspective arguing that entrepreneurs, and other artifacts, play an important role in this process (see Stack and Gartland, 2003; Garud et al, 2010). Garud et al

(2010) offers the term “path creation” to describe this more behavioral process where the self-reinforcing mechanisms are “strategically manipulated by actors” (Garud et al, 2010, p. 769). It is within this context that the “path” becomes “modified” by other forces (Puffert, 2024, p. 2500). These modifying forces can take different forms, such as the strategic actions of interested future players, or perhaps the changing future competitive conditions that make previously less critical elements in the original design even more important for future success

The role of entrepreneurial behavior in the path dependence (or path creation) argument is interesting, and not fully developed. The notion of the entrepreneur as an economic force is grounded in Richard Cantillon’s use of the term “undertaker” in his 1730 treatise, *An Essay on Economy Theory*, a term that was later translated into French as “entreprendre”. Entrepreneurship-like economic behavior, and the desire to improve, is not only a natural and noble human instinct, discussed as far back as Xenophon’s *Oeconomicus* (c. 401 BC) but is also the primary force behind continuous economic growth, an argument first offered in a comprehensive manner in Jean-Baptiste Say’s *A Treatise on Political Economy* published in 1803. These powerful and natural forces are why economists, such as Joseph Schumpeter and Wilhelm Ropke, who viewed entrepreneurial behavior as the disequilibrating key to economic and social growth, believed that both Keynesian economic theory and socialism, with their grounding in long-run equilibrium and mostly anti-entrepreneurial platforms, were neither theoretically correct nor historically accurate (see Galbraith and Stiles, 2023 for full discussion of this issue). Yet path dependence it seems, by its very nature, has an underlying assumption of equilibrium (e.g., Jackson and Kellman, 2012).

The strong theoretical connection between technological innovation and entrepreneurship was somewhat later in development, generally in the early to mid-20th century. For example, Joseph Schumpeter (1911, 1942, 1949), Murry Rothbard (1962) and William Baumol (1968, 2010) all saw the importance of connecting the natural instinct of entrepreneurship with the disrupting nature of technological innovation. Thus, from a path dependence point of view as applied to technologies, entrepreneurs will contribute to the commercialization of the initial design, that is, there are technological and competitive reasons behind the innovation - not a random accident as suggested by Arthur (1983) and David (1985). While certainly not all inventors are entrepreneurs, nor are all entrepreneurs inventing new technologies, the entrepreneurial mindset in both small and large organizations is what allows inventions to be developed, funded, and ultimately brought to the marketplace. Thus, entrepreneurs will always be seeking new technologies to break the equilibrium conditions of path dependence, thus at least shortening the time of the equilibrium cycles, particularly within relatively free markets.

Regardless of whether one takes a strict or more behavior orientation of path dependence, the importance of QWERTY as one of the premier case examples of path dependence for many cannot be understated (Puffert, 2024). For some, the notion of path dependence in general, and QWERTY specifically has become part of a proxy war on the role of government in the economy (Arthur, 2013, p.1186). For example, Krugman and Wells (2006) in their introductory economics textbook define the QWERTY problem as 'an inferior industry standard that has prevailed possibly because of historical accident' (p. G-12). In an earlier treatise Krugman was even more direct in his attack on market-based economies, noting, 'in the world of QWERTY one cannot trust markets to get it right' (Krugman, 1994, p.235). Lewin (2001) argues that QWERTY's alleged inferiority has become part of the conventional wisdom and has fed into much legislative and antitrust debate (p.67). On the other side of this proxy war, Liebowitz and Margolis (1990, 2013) argue there has been a lack of persuasive evidence that technological standards in general and QWERTY in particular have led to market failures serious enough to warrant the strong policy positions taken by some proponents of the so-called 'QWERTY problem'.

In fact, the QWERTY problem is both powerful and perplexing at many levels, particularly since it has survived various generations of typewriter designs, computerized word processing, and more recently, programmable keyboard technologies. And while there has certainly been a fair amount of debate about QWERTY in the past, its development is still poorly understood, particularly when attempting to understand its role in the overall final typewriter design and the resulting competitive, technological, and intellectual property strategies employed by its original inventors.

It is also relevant to note that its international variants, such as QZERTY (e.g, Italy), AZERTY (e.g., Fance, Belgium) and QWERTZ (e,g., Germany, Poland) , have also been dominant for over 140 years. These international variations have also been viewed under the lens of path dependence routines (Reinstaller and Hölzl, 2009, p.1021). Similar to the QWERTY layout, there remains little understanding of how these international variations were also developed. Gardey (1999), for example, found that in France the first model of the Adler typewriter was marketed in 1898. It was described in 1901 as having a QWERTY keyboard, but had changed to AZERTY by 1911, although no record of this evolution has been located.

Procedures and Method

To examine this strategic issue, we employ a combination of historical research methods. First, we examined archived letters between the various individuals involved with the Sholes's early typewriter. We photographed, indexed, analyzed and annotated approximately six hundred personal and business correspondences, financial records, patent applications, and legal documents between Sholes, his partner James Densmore, and other individuals and organizations, such as Remington, involved in the early typewriter development. These documents are known as the James Densmore Collection located in the Milwaukee Public Museum. The collection was donated to the museum in 1979 by Priscilla Densmore and includes various documents from 1854 to 1935. For our analyses, we concentrated on all the correspondences and documents from 1854 to approximately 1895, to find references to their competitive thinking regarding typewriter development and keyboard design. Surprisingly, there are only a few relatively minor references to keyboard design in the hundreds of their correspondences about typewriter design. This silence must therefore be interpreted from a broader understanding of the combined nature of the typewriter design and the complementarities of the associated intellectual property as discussed further in this paper.

Second, we extend prior QWERTY discussions by theoretically examining the engineering problems of the early Sholes design, applying an infrequency principle of letter matching, and then considering the strategic necessities of maintaining the complementariness of the intellectual property embedded in QWERTY. Understanding the strategic importance of IP complementariness that appears part of Shole's original strategy significantly extends Kay's (2013), Arthur's (2013) and Puffert's (2024) more recent discussions of QWERTY. Finally, similar to prior studies measuring keyboard efficiency, we examine common biagrams and trigrams to understand the longevity of the QWERTY design, particularly given the modern world of keyboard remapping programs and the development of rollover techniques used by modern typists using computer keyboards. It is our hope that by employing these various research methods that the issue of QWERTY can be decoupled from future discussions of path dependence and market failures and put into the category of a brilliant entrepreneurial IP strategy.

The original QWERTY design was near optimal.

We know that Sholes earliest design for the keyboard was a simple alphabetic, ABCDE design (Current, 1954, p. 44). It is well known, however, that Sholes had a serious problem with his early typewriter design – jamming. Unlike the 'visible' print mechanical typewriters that were sold in the 20th century, the early typebasket machine was a different design. The format was developed in 1872 by Christopher Latham Sholes working with his partner James Densmore. This basic relationship between format and hardware remained essentially unchanged with minor modifications over several subsequent models by Remington, who licensed and manufactured the early design. Figure 1 shows a stylized top elevation representation for the keyboard and typebasket of the later (1896) Remington No. 7. The letters on the keyboard were printed with typebars, metal strips with the character to be printed on their ends. The typebars hung down in a typebasket forming a shape rather like an ice cream cone with the bottom half cut off. When a keyboard key was struck, the corresponding typebar swung upwards inside the cone to hit the appropriate point on the printed page. In this design, the typist could not see the actual imprint on the paper; thus, the Sholes (and other designs of the time) are essentially 'blind' typewriters. Why develop a "blind" typewriter, when a "visible" typewriter is obviously more user friendly in terms of speed, accuracy, and corrections, is an interesting question in itself, but not the focus of this paper, which addresses QWERTY. To simplify Figure 1 we have represented all non-letter characters such as numbers and punctuation with an asterisk in the respective cases.

How QWERTY solved the jamming problem

A problem that Sholes faced in early typewriter design was that adjacent typebars in the typebasket tended to jam (see Joyce and Moxley, 1988, for example). While many writers have noted the jamming problem of the early typewriter design, and that the keyboard design was somehow created to address these issues, until Kay (2013a) nobody could describe the actual solution provided by QWERTY. For example, Rehr (1997) commented that to deal with the jamming problem, 'all Sholes needed to do was separate the letter pairs by at least one type bar.' (Rehr, 1997, p.4). While this might have relieved some of the jamming, Rehr's solution was not near optimal. What Sholes did to solve Rehr's problem was more elegant than trying to separate frequent letter pairs. With 26 letters and only 44 typebars (42 in the later Remington No. 7), some letters had to be placed next to each other on the typebasket. What Sholes did was to ensure that cases where letter pairs had to be next to each other on the typebasket they were infrequent letter pairs that were rarely found together in the English language.

The cases where letters were adjacent to each other on the Remington No. 7 typebasket can be seen in Figure 1 as being contained within the string of letters QAZSXDCFVGBHNJMK. It is extremely difficult at first sight to think of many words that contain letter pairs associated with that sequence read in either direction (e.g. QA or AQ; FV or VF, etc.). Using texts that would have been popular in Sholes time, Kay (2013a) showed that the 1873 version of QWERTY was near-optimal in separating letters on the typebasket that might be encountered together on the printed page. Using Mark T12wain's 145,000 word 'Life of the Mississippi' there are only 146 events found where words contained letter pairs that were also adjacent on the typebasket, or about one such occurrence every 1,000 words. This contrasted with a similar experiment using ‘Life of the Mississippi’ with the Dvorak keyboard format which resulted in 2358 such pairing events, about 16 times more frequent. An alphabetic, ABCDE, format results in an even much higher incidence of paired events, all of which could cause more jamming. This clearly demonstrates that given the typewriter technology of the time, QWERTY was superior to Dvorak in terms of format/device compatibility expressed in terms of its ability to minimize or avoid jamming issues. QWERTY was neither an accident of history, nor an inferior standard given the technology of the time.

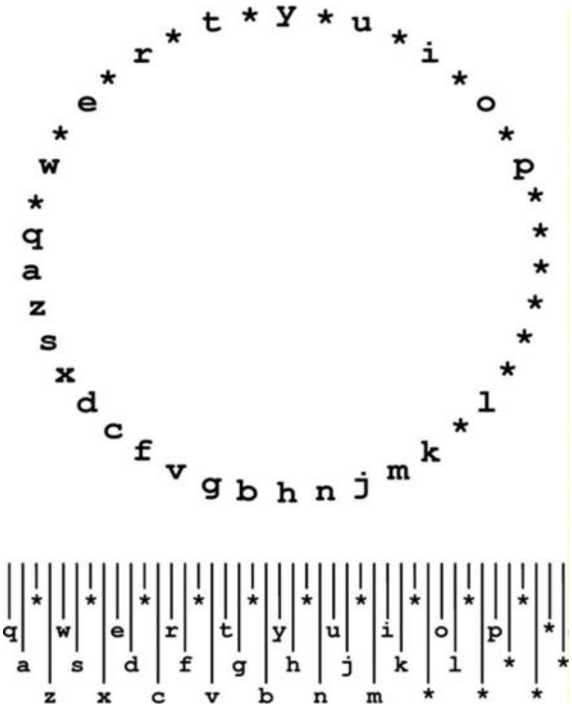

Figure 1: Remington no.7 keyboard and typebasket

The competitive importance of typing speed

Many authors have mistakenly suggested that QWERTY was designed to slow the typist in order to reduce jamming, and that the inventors, Sholes and Densmore were not interested in typing speed. This myth continues into the modern era. In fact, typing speed was a critical competitive success factor in the early typewriter market. But typing speed among different users also requires standardization. How Sholes did pursue this objective? The closest to an authoritative account of the development of the typewriter and the roles played by Sholes and those associated with him was set out by historian Richard Current (1954).[1] Current’s account indicates that by early 1871 Sholes’ successive models were still using an alphabetical layout for the keyboard (Current, 1954, p. 44), but by late 1872 this had been radically transformed by Sholes and Densmore into the first version of QWERTY. This evolutionary process of keyboard design is clearly referenced in a typed correspondence from James Densmore to his stepson, Walter Barron on November 5, 1872. He writes,

> Now about the change of key-board. This is the second letter I have tried to write with this machine. When I began, it was as new to me as if I had never learned any one. And there was this against it – I had to unlearn as well as learn. But now, at the close of this letter I am beginning to get quite familiar with it. So I am confirmed it makes but little or no difference in fact about it. Of course, it is better to have them all alike, but the change was better to be made or not. (Densmore Collection, Correspondence 11/5/1872).

It is also clear from this letter that James Densmore recognized the need to standardize, and not change the keyboard design much more. Frustratingly, James Densmore does not say in this letter why the change in keyboard was made, most probably for trade secret issues discussed later. It is quite likely that this letter marks the end development of QWERTY, but it also notes that Sholes evidently made many modifications to the keyboard (and typebasket) before this time. In a long letter from James Densmore to his brother, Amos (dated 5/20/1876) he talks about tinkering with keyboard designs as early as March, 1870, which is consistent with Current's (1954) date of settling on QWERTY by late, 1872.

> I think in March 1870 we made a machine … our 'space-key' was a blank key, in shape and size just like one of the type-keys, and put near the middle of the bottom or front row. (Densmore Collection, Correspondence 5/20/1876)

Most of the later correspondence between Sholes and Densmore discussing keyboard design focuses on mechanical processes and weight. However, there were later discussions to improve the keyboard design (increasing number of rows, number of keys) that would have certainly altered the QWERTY design (Densmore Collection correspondences dated, 2/11/1877, 6/27/1877, 9/10/1877, 11/24/1877). These considerations appear to be motivated by competitive typewriter designs, but it does indicate that QWERTY had not really become a universal standard by 1877. Nothing appears to have come of these alternate designs, however.

So while Sholes was primarily responsible for many of the other technological developments that were incorporated into the typewriter, the answer to the question as to who developed QWERTY is that it evidently was jointly developed and agreed upon by both Sholes and Densmore. Even though QWERTY is about the only major element of these endeavors to survive to the present day, at the time it would have been just one more technical fix out of numerous others that Sholes and Densmore were grappling with to make their machine work. Also, Sholes the main inventor and Densmore the promoter and financier both needed each other and would have had incentives to share the secret and motivate the other to keep committed to an enterprise which at more than one point looked fairly hopeless. We shall see later that Sholes was aware of the principle and indeed continued to apply it, but for the above reasons it is probable that Densmore was also aware of it.

When Densmore brokered the deal to produce Sholes' typewriter with Remington in 1873, Remington made some fine tuning to QWERTY which David (1985) cites as including placing the R in the top letter line, thus 'were assembled into one row all the letters which a salesman would need to impress customers by rapidly spelling out the brand name TYPE WRITER' (David, 1985, p.333). This is unlikely since Current (1954) also provides strong evidence that it had been Densmore and not Sholes who coined the name 'typewriter', as a single word and unhyphenated.

The application of the rule to QWERTY from the 1872 version onwards meant that QWERTY proved highly efficient in absolute terms in that it all but eliminated the typebar jamming problem arising from neighboring typebars on the typebasket being typed in succession. It also led to QWERTY being highly efficient in relative terms in that it demonstrated significantly superior performance compared to alternative formats such as the alphabetic (ABCDE) format that Sholes started with, or even the Dvorak format had that been available in 1872. The rule also meant QWERTY achieved levels of performance in those terms that simply would not have been feasible had the popularly believed method of using a list of frequent letter pairs been used instead. It also explains the placing of the vowels, including why 'E' and 'I' are the only two letters missing from the alphabetic string DFGHJKL in the third row on the keyboard and why 'Q' and 'A' are next to each other on the typebasket. All this is consistent with deliberate development and application of the infrequency principle, with Sholes (and possibly also Densmore) being aware of the principle and applying it.

While the infrequency principle was most certainly known to Sholes, and possibly also Densmore, there must have been some awareness of the principle in Remington itself, as evidenced by later modifications. This was not surprising; when the initial deal was made with Remington the company's representatives expressed only mild interest, Sholes and Densmore were running out of funds and Densmore in particular was eager to get their typewriter manufactured 'at almost any cost' (Current, 1954, p. 65). On Densmore's side, this incentive was heightened by his retaining a financial interest in QWERTY's success in a contract with Remington; Sholes was to sell his rights for a fixed sum in 1873 (Wershler-Henry, 2005, p. 70). But Sholes stayed active in typewriter designs even after his Remington deal.

Reviewing the hundreds of correspondences within the Densmore Collection also reveals that typing speed was a major concern to the inventors, particularly in the 1877 and 1878 period when QWERTY was ultimately revealed as a final design standard. For example, Sholes discusses hypothetical typing speeds when he writes to Amos Densmore about a competitor's typewriter design in 1877.

> Mr. Yost speaks of his making an invention in the stringing which will permit working a hundred words per minute. Perhaps he has, but how he is going to find out that it will work a hundred words a minute, I do not exactly know (Densmore Collection, Sholes correspondence, 2/14/1877).

It is interesting to note that the Yost 1 Typewriter introduced in 1887 had a keyboard design that somewhat resembled QWERTY. Sholes then writes to James Densmore a week later, '…nothing it seems to me, can beat the manner in which the machine works. I am prepared to believe that it can be worked at the rate of two hundred words per minute, and if you do not believe it I want you to prove to the contrary.' Then again, on April 11, 1877 Sholes writes to James Densmore, 'I know of no reason why a machine of 100 types is not just as feasible as one of 30 – and know of no reason why one of 100 should not work as well as one of 30. There is no necessity for making a machine to test that point.' Later in 1877, the inventors are discussing design options, including an oscillating wheel machine. Sholes writes to James Densmore,

> Just think a moment – assume we can get 60 words per minute with our machine. What does that require? It requires 6 signals (or letters with space) per second - or 1/6 of one second to each letter. Now 1/6th of one second is an infinitesimally minute space of time And how little of that minute space of time does one have to lose to slow up the results amazingly. If you have a machine which loses 1/12 of a second on each signal, you have only 30 words per minute. While you have lost apparently nothing in the speed of the machinery, you have lost in fact 50 per cent of the result. You know your machine and the mechanism by which such speed is produced – the blow of the finger and the print of the type are so nearly instantaneous that no one can detect the difference (Densmore Collection, Sholes correspondence, 9/17/1877)

By 1878, the inventors appeared more realistic as to the actual, normal typing speed of their technology. It appears they clearly recognized that the mechanical exercise of pushing the typebar down limited typing speed more than the layout. In an April 16, 1878 letter to James Densmore, Sholes uses a 25 words per minute standard. He expands this a little by 1879, where he writes 'No person can get over 30 words a minute out of our machine, if obliged to carry the finger deliberately to the bottom of the stroke many times.' (Densmore Collection Correspondence, Sholes to James Densmore, 9/16/1879).

A decade later, Sholes was starting to get concerned that he was now losing a technological advantage related to speed. He writes in 1887, 'I have more fear of failing for speed than anything else, I do not hope to get the Remington or the Caligraph speed. I do hope to get a practicable speed and then to fetch up so to speak on other qualities preferable to the (Remington) and (Caligraph).' But Sholes still sees speed in the range of 30 words per minute as a standard, 'I am tolerably sure a light-fingered party, after a little practice, will get 30 words per minute. I got over 20. If it goes no further this, with its cheapness and other good qualities ought to give it some value. . . ' (Densmore Collection, Correspondence, Sholes to Amos Densmore, 9/14/1887).

This sequence of correspondences reveals two important points. First, speed was always seen as important by the early typewriter inventors, and second, all of the discussion of speed in the correspondences between Sholes and the Densmore brothers appear to revolve primarily around design, engineering, and mechanical issues – particularly the time it takes to push a key down and have it strike the roll. However, from these correspondences we also know that Sholes was continuing to 'tinker' with the keyboard design during the whole early development process.

It is also interesting to note that by mid-1880s, typing classes were being offered across the U.S.; and various touch-typing techniques were being developed using QWERTY, most notably by Frank McGurrin. Typing competitions were also common during this period, with experts achieving speeds in the range of 80 to 90 words per minute (Wyckoff et al, 1900). Observers of these early competitions noted that primary limitation on typing speed was mechanical in nature once touch typing was learned (Wyckoff et al, 1900, p. 8).

Trade Secrets, Complementarities in intellectual property and the early strategy of QWERTY

Almost all prior discussions of the QWERTY issues have overlooked the importance of intellectual property in its development, and the overall competitive strategy used by Densmore and Sholes. Protecting intellectual property (IP) can involve a variety of tools including patents, trademarks, copyrights and trade secrets. In the present context it is the distinction between patents and trade secrets that matters. The most obvious difference between patents and trade secrets lies in disclosure; 'a trade secret is some sort of information that has value because it is not generally known' (Risch, 2007, p.6). While a patent may be disclosed publicly and granted on a new and useful design or process for a limited period of time, a trade secret is information which may give a business an advantage over competitors who do not know or use it (Besen, & Raskind, 1991).

While patent and copyright laws have long history dating back to the England's 1624 Statutes of Monopolies (patents) and the 1710 Statute of Anne (copyrights), Kapczynski (2022) argues that the first comprehensive legal cases of trade secret law started to rise in the middle 19th century, noting that 'in a series of common law cases, courts began to protect business secrets in new ways, both enforcing contracts that once would have been seen as impermissible restraints on trade, and treating business and trade secrets as rightfully subject to a certain kind of ownership.' (Kapczynski, 2022, p. 1383). It has been noted that modern trade secret laws developed in England during this time primarily due to the accumulation of technical know-how and increased mobility of employees over the course of the industrial revolution. (Sandeen & Seaman 2017, p.835). Many of the very earliest trade secret cases also dealt with them as a form of property right (Cross, 1990, p.529) with *Newbery v. James* (1817) generally regarded as the first trade secret case in English law (Sandeen & Seaman, 2017).

These broader definitions of intellectual property rights beyond just patents appears to have developed more aggressively in the United States, reflecting the somewhat unique United States perspective at the time of protecting all forms of property rights with the rule of law (Moser, 2021). By the mid-19th century, for example, with the rapidly increasing industrialization in the United States, the high productivity of 19th century inventors, such as Thomas Edison, Samuel Morse, Alexander Graham Bell, and Nikola Tesla, and the overall expansion into the Western regions of the United States, there was an increased recognition of the need to protect the full range of intellectual property such as patents, copyrights, trademarks and trade secrets. The modem Anglo-American law of confidential information evolved about the mid-nineteenth century when cases began to deal with the theft of valuable commercial information (see Cross, 1990, p.526, footnote 4; and Pold, 2023, p.126). It is generally accepted that the first case to acknowledge legitimate action for misappropriation of commercial information of value was *Morison v. Moat* (1851) (Cross, 1990, p.526, footnote 4). This also created the legal position that injunctive restrictions against former employees regarding trade secrets were permissible and not restraints of trade or labor (Fisk, 2000, p.457) and allowed employers to protect against the revelation of proprietary information by past or present employees (Fisk, 2000, p.442).

Trademark and copyright law also developed in tandem with other forms of intellectual property protection and also became more extensive following the conclusion of the Civil War in 1865. While Justice Joseph Story of the U.S. Supreme Court recognized that copyright was private property that should be protected against "piracy" in 1841 (*Folsom v. Marsh*), it was later in 1879 that the U.S. Supreme Court fully recorded that Congress was authorized under the Copyright and Patent Clause to secure "the fruits of intellectual labor" in patents, copyrights and now trademarks. (Moser, 2021). It is these cases (*U.S. v. Steffens, U.S. v. Wittemann, U.S. v. Johnson*), now known as the "Trademark" cases, that extended the protection of the law to trademarks registered in the Patent Office. This was an important development, since unlike patents and copyrights, trademarks according to Court's opinions, "has no necessary relation to invention or discovery" (100 U.S. at 94), and that they are "important instrumentalities, aids, or appliances by which trade, especially in modern times, is conducted" (100 U.S. at 9). Thus 19th century US courts saw an increasingly broader definition of intellectual property as having both foundational moral and legal justification, which, in turn, sets the stage to understanding the developing legal perspective of trade secrets (Moser, 2021; Bone 2015), and its use as a competitive strategy.

In the case of trade secrets, developing new laws to protect employers' those trade secrets in the mid-nineteenth century meant that the judges effectively created a new form of intellectual property in terms of the protection of ideas, and saw the issue as essentially one of economic policy (Fisk, 2000, p.445). But the viability of trade secrets in the mid-19th century could vary across technologies. For example, it took Isaac Singer 11 days in 1850 to reverse-engineer Lerow and Blogett's sewing machine, and then protect Singer's version with patents. By contrast, mid-19th-century inventors could rely on secrecy for chemicals and dyes because such inventions were effectively impossible to reverse-engineer in those days (Moser, 2007, p.8). In the United States, The *Peabody v. Norfolk* (1868) is often cited as the first court case that established trade secrets as a form of intellectual protection in modern terms (Kapczynski, 2022), but in the United States, individual States regulate trade secret law independently. Thus, by the time the typewriter was being developed in the 19th century, trade secret law was still somewhat in its infancy compared to patent law, but both viewed as important elements of intellectual property. In fact, it was not until the publication of the Uniform Trade Secrets Act (UTSA) in 1979 that the U.S. Federal government attempted to standardize trade secret laws (the UTSA is not binding, but rather must be adopted by the individual states).

. In general, information is considered a trade secret if it is commercially valuable, it is known to only a limited number of individuals, and there are reasonable efforts to keep the information secret. The relative ease of reverse engineering mechanisms, as in the Singer case, makes the QWERTY relationship with typewriters even more important to understand. From a strategic point of view, keeping something important secret when a competitor might copy it has always made sense, particularly when the secret is not easy to reverse engineer. But the potential importance of complementarity in terms of IP protection has not been really fully recognized until recently, indeed it has been more usual to portray forms of IP protection (including patents and trade secrets) as simply substitutes for each other (e.g. Friedman, et.al. 1991; David 1993, p.31; Fisher and Oberholzer-Gee, 2013, p.160). Where complementarities at the level of IP protection have been recognized, it has tended to be along the lines of several patented inventions combining as economic complements to produce one product (e.g. Cohen et al, 2000, p.22).

It is now clear that potential complementarities in IP protection can extend across forms, can include trade secrets, and indeed have been actively sought by firms in different industries from the early years of industrialization to the present day. Arora (1997) cites several examples from the late 19th and early 20th century of chemical firms combining patents with secrecy, for example by patenting several compounds but retaining secrecy over the composition of specific dyestuffs. In other cases, decoy patents could act as chaff and help camouflage which patents were really intended to add commercial value. More recent times have seen examples of very different products and processes which have patented some elements of the underlying technology while keeping other aspects secret, such as Pilkington's float glass technology (Al-Aali and Teece, 2013, p.26), GEs process for making industrial diamonds, a hormone therapy drug produced by Wyeth, and C&F's technology for freezing ingredients for pizza toppings (Jorda, 2013, pp.28-30). Mazzone and Moore (2008, pp.57-9) note several ways in which in which patent holders may use undisclosed information strategically and to their advantage, while Sherwood (2008) notes that the contribution of many research joint ventures can be in the form of a combination of patents and trade secrets.

The exploitation of complementarities can extend to other forms of IP protection, for example Henkel et al (2013, p.67) note the case of a flash drive where the binary code was copyrighted while the source code was kept secret. Even more complex combinations are possible, for example different aspects of a single data processing system or a biotechnological diagnostic kit can be protected by a phalanx of complementary patents, copyright registration, trademarks and trade secrets (Jorda, 2008, p.13). At strategic level, Ottoz and Cugno (2008) explore the optimal patent/secret mix for complex products, while at policy level Ottoz and Cugno (2011) develop a model of the ideal scope of trade secret law where a technology comprises two complementary components, one of which is patented, and one is secret.

We argue that QWERTY was also part of a sophisticated IP strategy employed by Sholes and Densmore. The first clear example of the QWERTY design representing a legal document was in Sholes patent for his 'improvement in type-writing machines' that was eventually published as US patent 207559 on August 27, 1878. The patent application was filed on March 8, 1875.

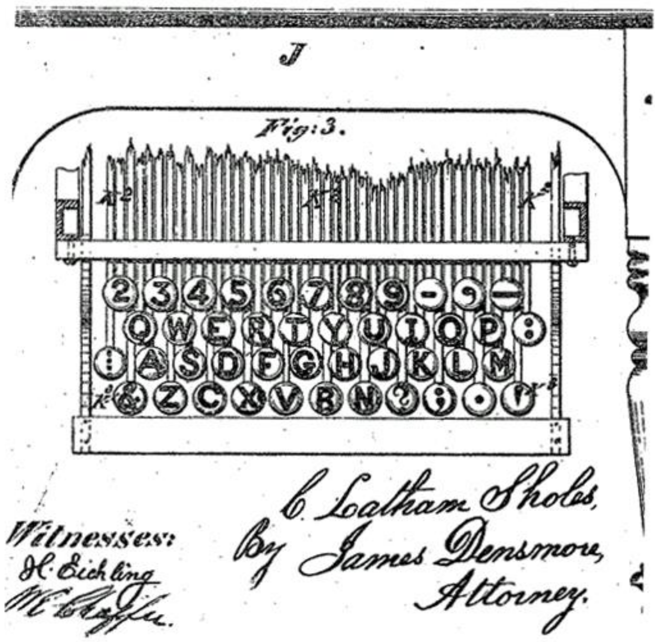

Figure 2: QWERTY in U.S. Patent 207559

Many people mistakenly confuse the appearance of QWERTY in U.S. patent 207,559 as a patent for the QWERTY format. However, a careful reading of the U.S. patent 207559 does not mention QWERTY; the claims in the patent all address mechanical issues related to the typewriter. The lack of claims related to QWERTY in U.S. patent 207559 is critical and has never really been addressed in the literature. This is important since typewriter keyboard designs can be patented. The Dvorak and Dealey patent issued in 1936 (US patent 2,040,248), for example, has thirteen claims explaining in detail how the typist hands move on the keyboard, and the subtle logic behind the design. A search of the U.S. patent office for ‘typewriter keyboards’ results in a number of other proposed designs over the decades. U.S. Patent 5,124,702 issued to van Ardenne and de Zwijgerlaan in 1992 offers a redesigned layout with multiple claims as to its efficiency. There were also other proposed designs around the time of the 1936 Dvorak patent. U.S. Patent 2,080,457 issued in 1937 to Raymond Bower of the Burroughs Adding Machine Company, offered a WCUMGP design, arguing that his design was more efficient in typing given frequent letter combinations.

So why was QWERTY not patented and why was QWERTY not discussed in the hundreds of correspondences between the inventors? The reason is the complementary asset of the infrequency principle combined with the QWERTY design, a trade secret that incorporated both issues in combination. Patenting was not an option for Sholes’ infrequency principle – the key to his successful typewriter design. The US Supreme Court had already ruled that an abstract idea such as the discovery of a new principle was not patentable but had to be embodied and brought into operation by machinery to produce a new and useful result (US Supreme Court. 1852)[5]. Sholes was acutely aware of the problem of patenting 'principles' (see also Sholes letter to Amos Densmore, 10/11/1877). The QWERTY keyboard design, however, embodied the infrequency principle into the typewriter design. The complementarity of patent and trade secret protection was not a choice for Sholes and his partners, it was a necessity if they were to defend their intellectual property successfully. Take away the patent aspect and imitators could have simply cloned his typewriter once it began to show commercial promise. Take away the trade secret aspect and rivals could have developed alternative formats using the infrequency principle. But to patent QWERTY would have required publishing the infrequency principle through patent claims. Instead, by showing QWERTY as a figure in US patent 207559, it established a clear 'prior art' of a standard so that nobody else could patent the design (although probably nobody could have argued why QWERTY was important without knowing about the infrequency principle). Likewise, a competitor using QWERTY without the Sholes type basket design or understanding the 'infrequency principle' would create jamming problems for any new design since the principle behind QWERTY cannot be easily reverse engineered.

Thus, not only was the QWERTY design an elegant and possibly optimal solution given the mechanical technology of the typewriter at the time, but it also needs to be considered a complementary asset to the infrequency principle that underscored the early typewriter design. Recognizing the complex relationship between the patentable typewriter design components and the underlying trade secret of the infrequency principle, Sholes and Densmore, and later the Remington Corporation, used a highly sophisticated strategy of obtaining optimum performance at the time, while implementing the underlying principle behind the design through the non-patented QWERTY, a keyboard design that quickly became part of the public domain.

QWERTY and later typewriter changes

The above discussion clearly demonstrates that QWERTY was not an 'accident of history', or deliberately an inferior design, but actually an elegant and near optimum solution of entrepreneurial effort in both its design and application of IP strategy, given the designs of the day. But clearly technology evolves, and by the 1900s, the basket type design had given way to the up strike, or 'visible print' typewriter which became the dominant design from 1900 until the introduction of the IBM Selectric typewriter with a 'golfball' typing element in 1961.

. Sholes filed a patent for a visible print typewriter (U.S patent 464,902A) in 1889, which was subsequently issued December 8, 1891. However, the first commercially available visible print typewriter seems to have been the Williams typewriter introduced in 1895 and the Oliver typewriter in 1896. It is interesting to note, however, that Remington continued production of the older 'blind' typewriter until 1915. It should be obvious that a 'visible print', up strike technology would be a better technology than the blind basket typewriter in terms of typing accuracy and corrections. Why the early typewriter designs were not 'visible print' is an interesting question, and beyond the scope of the present discussion. However, for the 20 or so years that the blind basket technology dominated the typewriter marketplace, QWERTY had an absolute advantage due to the associated intellectual property of the infrequency principle that made the up-strike technology work.

The QWERTY keyboard, however, transitioned into the new 'visible print' typewriters, although the original infrequency principle driving the earlier design was no longer as critical. However, with the newer up strike, visible print typewriters still had jamming problems – essentially when two bars occupied the same space on the roll. Thus, the sequential timing of the keystrokes became more important to reducing jamming problem.

While QWERTY was clearly designed by entrepreneurial minded investors to solve a critical problem of the 'upstrike' typewriter technology by employing an effective strategy of complementary IP and trade secrets, the second question of path dependence remains – why has QWERTY remained the dominant keyboard design after the transition to 'visible print' typing technologies?

In spite of many patented keyboard designs, the 1936 Dvorak keyboard presented the most comparisons over the years. Much of the basis for the supposed superiority of Dvorak over QWERTY cited by David (1985) and others is based on format/user compatibility issues, notably advantages claimed in speed of touch typing. However, there are several difficulties with David's argument that QWERTY was the wrong system for the industry to standardize around. First, as Liebowitz and Margolis (1990), note, the empirical evidence often cited to argue that Dvorak really was superior to QWERTY on format/user compatibility grounds is questionable. We extend this discussion considering modern keyboard typing research.

Over the years, there has been an almost obsession in some circles with arguing other keyboard designs should replace QWERTY. Hiraga et al (1960) note as early as 1893 there were objections to QWERTY. In fact, an October 19, 1892 correspondence to Mr. Densmore shows a Merritt Typewriter with a different keyboard layout from QWERTY (Densmore Collection). Dvorak and Dealey, in particular, were highly aggressive in promoting their particular keyboard design, even writing a book about it (Dvorak et al, 1936). Dr. August Dvorak also supervised several government and university sponsored keyboard studies during the 1940s which found QWERTY inferior (Foulke, 1961; Buzing, 2003; Strong, 1956) – a perhaps not surprising conclusion since the inventors would receive significant license revenues from their patented layout if adopted. Other early studies, however, appeared to support the advantages of QWERTY (Strong, 1956). However, many of these early comparison studies were based are remarkably small samples, and in some cases, a conclusion based on a single professional typist.

A 1944 U.S. Navy study, which was later found to be conducted and written by Lieutenant Commander Dvorak (Foulke, 1961, p. 103), indicated that QWERTY typists trained on the Dvorak format, develop their typing skills, "eleven times as rapidly as does the improvement of skill on the Standard Keyboard." (U.S. Navy, 1944, p. 26). This report subsequently resulted in the U.S. Navy ordering several thousand typewriters with the Dvorak format, which was subsequently blocked by the U.S. Treasury Department (Buzing, 2003). Later, in the early 1950s, proponents of the Dvorak layout, or 'simplified keyboard', had approached both the U.S. government and the American Standards Association arguing for a change in keyboard standards. By 1954 the U.S. government was considering a change to the Dvorak keyboard layout standards for Federal employees – a form of government intervention in standard setting that some strict path dependence advocates might applaud. A study was commissioned and subsequently published in 1956 by the General Services Administration. Using a carefully controlled and unbiased study of 20 typists, the lead researcher, Dr. Earl Strong, concluded that, 'Simplified Keyboard typists showed less control (accuracy) than did the Standard keyboard typists on both 1-minute and 5-minute writings for the total period of the experiment.' (1956, p. 40), and that, 'A recommendation for the adoption of the Simplified Keyboard for use by the Federal Government cannot be justified based upon the findings of this experiment (1956, p. 41). This report appears to have put an end to any governmental interference with the standard.

Second, even when touch typing began to be widely adopted towards the beginning of the 20th century, there would have been little point in pursuing marginal increases in typing speed if the user repeatedly encountered format/device compatibility issues (and jamming problems). This is critical since typing classes were being offered as early as the 1880s, while full blown secretarial schools were in place by WWI. Certification of early professional typists often used a 30 or 40 words per minute standard but with an emphasis on few errors, since fixing errors was both time consuming and unattractive to the final product. Thus, from a job market point of view, there was no advantage of typing much faster than the minimum speed required to obtain a typing certification from a secretarial school.

Third, modern ten-finger touch typing that Dvorak was designed for in 1936 was very much a later development, and indeed as late as 1887 (fourteen years after Remington sold Sholes' first typewriters) an editorial in a trade journal was still arguing that optimal typing speed was achieved by using only the first two fingers of each hand (Wershler-Henry, 2005, p.232). With the advent of 'touch typing' modern research has also shown that only a small percentage of even trained typists actually use all ten fingers, and that self-taught typists using a variety of finger sequences can be almost as fast as trained ten-fingered touch typists (Dhakal et al, 2018).

Finally, the physical nature of typing also needs to be considered. With a traditional mechanical typewriter (until the invention of electric typewriters) the typist needs to use force to push down on a key (a major limiting factor related to speed, a point referenced by Sholes in correspondences as early as 1877), and that muscle behavior is different when using alternating hands versus the same hand. Research has long indicated that letter pairs typed with fingers from different hands are generally faster than letter pairs typed with fingers of the same hand (e.g., Hiraga et al, 1960; Salthouse, 1986; Dhakal et al, 2018). Typists also gain speed by moving hands and fingers in 'parallel' (Dhakal et al, 2018).

With the introduction of computers another change has been seen. Almost all modern word processing and gaming systems have the capacity of 'remapping' keyboard design. In addition, there are many 3rd party keyboard remapping programs available, such as 'Key Remapper,' 'SharpKey's and the open source software "Portable Keyboard Layout.' With keyboard remapping, the interest in redesigned keyboard layout has continued. The COLEMAK layout for computer keyboards, for example, was designed in 2006 by Shai Coleman, and is now reported as the 3rd most popular design, behind QWERTY and Dvorak. Its claim to superiority is based upon ergonomic and hand row jumping advantages. However, with modern computerized keyboards a new phenomenon known as 'rollover' is becoming more evident. Rollover is when a person does not release an earlier key before pressing a new key. Rollover performed on a traditional mechanical typewriter would likely cause jamming, but it increases typing speed when using computerized keyboards. Rollover techniques are much easier to perform in alternating hand scenarios, rather than using fingers of the same hand.

Why has QWERTY continued during this modern evolution? Possibly several reasons. Sholes was not only an inventor, but also a typesetter by profession. He was familiar with print type box designs, the importance of hand-eye coordination, the placement of frequent letters and letter pairs in the most accessible points in the print type box, and the importance of efficiency, speed and error reduction in setting type. QWERTY, while an elegant implementation of the infrequency principle, is not the only infrequency principal solution to the jamming problem of Sholes' early typebasket design. For example, the string of adjacent letters on the Sholes typebasket are all consonants apart from A sandwiched between Q and Z at the beginning, that is QAZSXDCFVGBHNJMK. A and S are dangerous because they form frequent letter pairs with many other letters, but they are safely neutralized between Q, Z and X with which they rarely couple. But the remaining string of letters to the right of these five are consonants that all form a class in which in each case there are many other consonants with whom they rarely couple. Sholes could have swapped around the order of these letters and some of these combinations would possibly be as efficient as QWERTY by creating an equal number of infrequent letter pairs on the typebasket.

We have explored several different combinations to implement the infrequency principle by making such swaps. Some swaps can still possibly optimize the infrequency principle that was important to the original Sholes typewriter design – for example, swamping V with J, now making eight new letter pairs FJ and JF, JG and GJ, NV and VN, VM and MV. These letter pair combinations are also highly infrequent in the English language. However, each such change would also change the keyboard given the mechanics of the typewriter. We have explored the efficiency component of several different combinations to implement the infrequency principle by making such swaps.

Alternate hand frequencies is considered one of the primary predictors of typing speed (e.g, Dhakal et al, 2018). Throughout the history of typing research, there have been countless studies that evaluate keyboard design, such as QWERTY, Dvorak, and alphabetical designs. These studies tend to follow two paths, either measuring typing speeds of actual typists or creating an efficiency scale. One of the more sophisticated models is the application of Fitts' Law to predict movement time for various human activities (Fitts, 1956). Applying Fitts law to keyboard design indicates that Dvorak might be slightly more efficient than QWERTY but QWERTY scores higher on the benefit of alternate hand use (Buzing, 2003). However, these prior typing efficiency scales generally focused on bigrams, and did not examine letter trigrams, which appears even more important given modern "rollover" computer keyboard typing techniques. To analyze these possible combinations, we examined the alternating hand use using the ten most frequent bigrams and five most frequent trigrams. It is important to note that frequent trigrams are often actual words (e.g, the, and).

Using the University of Notre Dame listing of the most common bigrams and trigrams, QWERTY appears very efficient (six alternating hand bigrams, two bigrams with adjacent letters from same hand, and four out of the top five trigrams using alternating hands). Given our argument that QWERTY is actually a combination of maximizing the infrequency principle with Sholes' concern for efficiency and speed, we then examined ten different possible keyboard swaps that Sholes could have implemented that still maintained the infrequency principle; that is, the swap did not create frequent adjacent letter pairs. In each case QWERTY was equal or more efficient than other options in the use of alternating hand bigrams and trigrams. Other swaps, however, such as J for K, would result in potential jamming problems. Putting K next to N, for example, creates a single combination, 'NK', a relatively common bigram which violates the infrequency principle. And in this case, there is no gain in typing efficiency on the keyboard.

Finally, as a reference, we also examined the alternating hand use of other historical keyboard designs, such as Dvorak as well as designs from Bower (1937), van Ardenne and de Zwijgerlaan (1992), and the COLEMAK (2006). In each case, QWERTY appeared more efficient, primarily due to QWERTY's efficient use of alternating hand trigrams.

In more modern terminology, it appears that Sholes was solving a classic multi-objective optimization problem, where one goal represents optimization of the infrequency principle (which was required for the up-strike typewriter design) while the other goal represents typing efficiency and speed, something that obviously the inventors frequently discussed in their correspondences (e.g., Densmore Collection letters). A review of all possible combinations of adjacent pairs on the typebasket might reveal whether QWERTY actually represented a form of Pareto efficiency given the technology of the time, but it seems likely. While not having access to modern computers to work this out, it appears that QWERTY not only solved the early jamming problem in an elegant manner, but at the same time created a solution that provided excellent typing efficiency. Given Sholes background as a printer/typesetter and well as the inventor of the typewriter, one could assume during his years of tinkering with the keyboard design, he must have considered this issue of addressing two objectives at the same time. In fact, Current (1954) notes that Sholes might have started originally with the print type case layout as an early keyboard design [2].

Reading the various claims and arguments associated with various keyboard designs patents, such as Dvorak and Dealey's patent, van Ardenne and de Zwijgerlaan's design, Bower's keyboard and the more modern open-source COLEMAK design, the detailed and nuanced explanations for improvement in the patents and designs themselves provide the best answer – it is far too complicated to gain at best a minor, if any, improvement given the different forms of typing, such as experienced v. novice, ten-finger touch typists v. two-finger hunt and peck typing, and the introduction of ‘rollover’ typing on modern computer keyboards to remotely justifying a change. In addition, almost all the experimental studies that provide justification for alternate formats are based on speed, rather than jamming and errors/corrections, and use trained typists as their sample – who only make up a fraction of the actual keyboard using population. Dhakak et al (2018), for example, using observations from 136 million keystrokes from 168,000 volunteers found eight distinct classes of typists, each with their own typing style and needs. The largest group of typists they identified as ‘Slow Careful Typist’, where the possible incremental speed benefit from other keyboard designs become relatively meaningless.

In fact, the timeless nature of QWERTY does not appear to be a true path dependent equilibrium, but rather a sustaining phenomenon that is primarily equilibrium independent of its history. The design has withstood not only multiple competitive designs over time, but also user acceptance. However, perhaps the most compelling are the implications of the modern keyboard remapping programs that allow the individual user to rekey their computer keyboard to their own preferences and typing style.

Keyboard remapping is primarily used for two reasons. First, for one handed typing on larger screen Smartphones (Wang et al, 2023). For example, a number of proposed layouts have been offered for single-handed on-screen typing, such as TYPEHEX or minor variations of QWERTY, or ‘soft QWERTY’ (Pritom, 2015). The second remapping use tends to be by video gamers users not to change the basic QWERTY layout on a hard keyboard, but rather alter other keys such as Cap Lock, Esc, Ctrl, Shift and arrow direction keys to more efficient gaming and virtual reality use (Dyck et al, 2003; Schneider et al, 2019). Thus, even in light of modern keyboard remapping and the ability of individual users to design their own technology, QWERTY seems to not only survive, but absolutely dominates even modern computerized keyboard usage – and unlike Dvorak and others who filed patents around their designs, Sholes never intended to license or sell QWERTY.

Conclusions

Christopher Latham Sholes and his partner, James Densmore were not only inventors, but entrepreneurs in the classic sense. As revealed in the many hundreds of correspondences in the Densmore Collection, the two partners certainly had their professional disagreements, and near the end of their relationship developed an actual dislike for each other. But they also achieved their aim of creating what would have been at the time the ‘perfect’ type-writing machine in terms of the performance parameter that mattered at the time. QWERTY was only one of several possible embodiments of the infrequency principle, but it was that underlying principle embodied in QWERTY and ingeniously integrated with the hardware in Sholes' devices that really helped win the battle of the standards while at the same time clearly recognizing the typing speed was also critical to market success.

However, as an entrepreneur, none of this would have been possible had Sholes not used a judicious blend of complementary trade secret and patent protection from the beginning. This is a classic example of what Ottoz and Cugno (2008) describe as a sophisticated patent–secret mix strategy used in complex products. Most trade secrets, however, tend to be 'wasted assets' dissipating after an average of 3-5 years because of employee mobility and reverse engineering, though with some exceptions such as Coca Cola's recipe which has been secret for over 100 years (Jorda, 2008). Sholes infrequency principle had a useful economic life of about a quarter of a century before the development of up strike, visual typewriter technology made it obsolete, but it still stayed secret for 140 years despite the considerable interest in the provenance and genesis of QWERTY. In view of the central role that these issues played in the evolution of this standard, it also raises interesting questions for future research as to whether such complementarities may have played key but unappreciated roles in the development of other standards.

By showing how Sholes used his infrequency principle as a complementary form of IP we strengthen the conclusions of Kay (2013a) that QWERTY was a consequence of creative design rather than an accident of history. By examining Sholes' correspondences, we also demonstrate that he was acutely aware of the competitive aspects of typing speed. And given Sholes' background in type setting, he certainly had a deep appreciation of the principles of efficient hand/finger movement in selecting and setting type. With QWERTY, Sholes appeared to have ultimately settled on the most efficient keyboard design among a small class of other layouts that also addressed the infrequency principle. And this was all accomplished while developing a sophisticated strategy utilizing the complimentary nature of the different types of IP embed in the typewriter, from the patentable components of the machine to the trade secrets of the infrequency principle which had to be implemented through the keyboard format.

Given the changing nature of keyboard technology, the fact that there are many different classes of keyboard users, and the ability of QWERTY to not only withstand competition from many different keyboard designs, as well as user decisions (particularly in the modern world of keyboard remapping) clearly supports the conclusion that QWERTY is neither a 'paradigm case' of inferior standards nor a path dependent historical equilibrium that supports a path dependence argument. Instead, the QWERTY case is more consistent with the notion of path creation and brilliant entrepreneurial thinking that most likely was implemented to satisfy multiple customer objectives, some of which survived into the modern world. This is what has allowed QWERTY, and its various international variants, to withstand challenges from other potential design standards, such as Dvorak, over the past 140 years, and perhaps for many more decades in the future.

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[1] Current (1954) appeared to have examined some of the letters now known as the Densmore Collection prior to their gift to the Milwaukee Public Museum. The authors of this paper have spent several years with the Densmore Collection at the Milwaukee Public Museum, and it appears that Current may have had access to some letters that did not end up in the Densmore Collection. In addition, the Densmore Collection has many correspondences that Current probably did not have access to. In general, we could cross-check and confirm the references by Current (1954), but not always.

[2]. To analyze these possible combinations, we developed a simple keyboard efficiency measure where the number of the top ten most frequent bigrams using fingers from alternating hands would receive a point value of '1', and the number of alternate hand fingers to type the top five trigrams would receive a point value of '2' (frequent trigrams are typically actual words, and therefore weighted more), and non-alternating hands but using adjacent keys would receive a point value of 0.5. This type of alternating hand keyboard efficiency measure is appropriate for both experienced touch typists as well as typists using less than all ten fingers, and particularly important for typist using modern "rollover" techniques. QWERTY receives a score of 15 pts, while the Dvorak keyboard only scores 11 points on our scale, primarily due to fewer trigrams utilizing alternating hands with Dvorak. Other keyboard designs investigated scored equal or lower than QWERTY. We recognize that our discussion of keyboard efficiency is determined by what letter pair frequency list one uses. We used the University of Notre Dame list (https://www3.nd.edu/~busiforc/handouts/cryptography/Letter%20Frequencies.html) of most common bigrams and trigrams. Other projects, such as Project Gutenberg results in slightly different lists -- although the first ten bigrams, for example, are very similar they are somewhat in different order. In doing our comparison analysis, we looked for combinations that did not result in creating new significant frequency letter pairs using the SAS 'Heat Map' of bigram distribution (source: https://blogs.sas.com/content/iml/2014/09/26/bigrams.html). It should also be noted that Sholes attempted to invent a machine for typesetting in the 1860s, so he was definitely familiar with the various type setting boxes of 'job cases, such as the California job case.