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The QWERTY Problem

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Abstract

This paper reviews the emergence of the QWERTY standard which in turn has lent its name to what Krugman and Wells (2006) describe as the "QWERTY problem: an inferior industry standard that has prevailed possibly because of historical accident". QWERTY was neither inefficient nor an accident, it was engineered by Christopher Latham Sholes in 1873 to be as near-optimal as possible given the technology and user needs of his day. To achieve this, Sholes used a simple meta-rule that is obvious once articulated but which has not been publicly recognised until recently. Despite its general adoption as "paradigm case" in the literature on path dependence, the analysis here finds the evidence is not consistent with QWERTY being a path dependent phenomenon, nor does QWERTY provide any basis for policy prescriptions based on common interpretations of what constitutes "the QWERTY problem".

The QWERTY problem

1. Introduction

The QWERTY standard for keyboard formats has endured almost unchanged since it was first invented by Christopher Latham Sholes in 1873. However, in recent years it has not only continued to serve as a universal standard, it has found another role as the focus for a proxy war over the proper role of government in the economy. As Arthur notes:

> " …QWERTY, as a standard—or better as an example of what the market has served us up in the long evolution of one particular technology—has become in economics a focal point, a rallying point for a larger issue: whether the market can lock us into an inferior standard. And this itself is part of a still larger issue: whether the free markets of capitalist economies can drive us into inferior outcomes." Arthur (2013).

On one side of the debate can be found Krugman and Wells (2006), who in the glossary of their introductory economics textbook define; "**QWERTY problem**: an inferior industry standard that has prevailed possibly because of historical accident" (p. G-12)". The QWERTY problem has as its basis "in the world of QWERTY one cannot trust markets to get it right" (Krugman, 1994, p.235). Krugman and Wells' (2006) advise their beginning economics students; "Government can play a useful role both in helping an industry establish a standard and helping it avoid getting trapped in an inferior standard known as the QWERTY problem" (p.536) and also "in principle government intervention might be useful in moving an industry to a superior standard" (p.534) .

These clearly are major policy positions to take - or to extrapolate - from what is after all just a pattern of 26 letters, 10 numbers and some other characters. But despite the bullish sentiment expressed in Krugman and Wells about the potential role for government in such contexts, Krugman had earlier noted that economists in general had been more diffident about what kind of policy conclusions could be drawn from the world of QWERTY (Krugman, 1994, pp. 243-44). Despite that, Lewin (2001) notes that at least the idea of QWERTY's alleged inferiority has become generally accepted as established fact: "the conventional wisdom remains that such (alleged QWERTY-type) inefficiency is widespread and much recent antitrust activity (including the recent Microsoft case) and legislative policy discussion is based on that assumption" (p.67).

However, Liebowitz and Margolis (1995; see also 1900) argue there has been lack of persuasive evidence that any plausible case of sub-optimal lock-in has ever been satisfactorily documented, and they also question the historical evidence, the theoretical basis, and the policy implications drawn from the economics of QWERTY.

So QWERTY is important, not just in its own right, but through its co-option as what Lewin (2001) describes as "a paradigm case" (p.67) in this proxy war. As Kay (2013b) notes, the paradigm role QWERTY has played in the debate on the role of government in setting of technological standards echoes the paradigm role the lighthouse played in the debate on the role of government in provision of public goods. And if Liebowitz and Margolis are right and QWERTY may not add up to much of a paradigm case, this makes examining the claims made for it in the context of "the QWERTY problem" even more relevant today.

However, it is important to note that the paper here does not conflict with the basic mechanisms of network externalities and increasing returns leading to lock-in as developed in seminal contributions by Arthur (e.g. 1983) and David (e.g. 1985). On the contrary, the narrative here only makes sense in the light of these mechanisms and is dependent on these works as crucial foundations.

We look at the background to the QWERTY story in Section 2 before examining the role it has played in the path dependence literature in Section 3. We examine the reasons behind the genesis of the standard in Section 4. In the following three sections we look at the efficiency implications of subsequent events, first in Section 5 from the perspective of the invention of up-strike technology; then in Section 6 from the perspective of the invention of the alternative Dvorak format; and in Section 7 from the perspective of later developments. We consider some implications of our analysis in Section 8, and then finish with a short concluding section.

2. The QWERTY story

Christopher Latham Sholes invented QWERTY in the 1870s in his development of what was branded "the Sholes and Glidden Type Writer". He sold the rights to it in 1873 to E. Remington and Sons and it was eventually relabeled the No. 1 Remington (Wershler-Henry, 2005, pp.70-71). The QWERTY format developed in 1873 had four rows with eleven characters in each row and QWERTY takes its name from the first six letters in the second row in Figure 1.

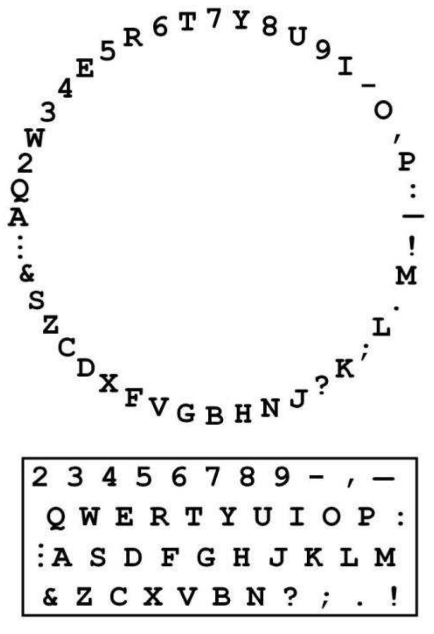

Figure 1: Sholes QWERTY keyboard and typebasket 1873
Source: Koichi Yasuoka and Motoko Yasuoka (2009)

Typebars helped transfer the 44 characters on the Sholes/Glidden or Remington keyboard to the printed page. A typebar was a long metal strip with a character to be printed at the end. The 44 typebars hung down in a circular typebasket inside the typewriter and the arrangement of the characters on the Sholes/Glidden typebasket is shown at the top of Figure 1. This was what has been since defined as up-strike (or up-stroke) technology in which pressing the appropriate key on the keyboard swung the corresponding typebar up to the printing point on the page. However, because the printing point was located under the paper carriage it was invisible to the typist, this invisibility being a feature not just of the Sholes Glidden but of the other up-strike machines of the time. A serious problem was the tendency of typebars to jam (David, 1985, p.333). Joyce and Moxley (1988) noted that "adjacent typebars tended to jam when the keys for these typebars were struck in rapid succession by 'hunt and peck' typists" (p. 34, italics added) and Rehr explains why:

> "To understand the clashing problem, try wiggling your index and middle fingers. See how they rub together? The same thing happened with any two adjacent type bars on Sholes' developmental machine…. Now, wiggle your index and ring fingers. Notice how they don't clash at all … It appears that all Sholes needed to do was separate the letter pairs by at least one type bar." (Rehr, 1997, p.4, italics in original).

In short, the problem of adjacent typebars being liable to jam when typed in close succession was a fundamental engineering problem for Sholes.

David (1985) describes how Sholes' 1873 QWERTY reflected not just years of his trying to reduce the frequency of these typebar clashes but also "assembled into one row all the letters which a salesman would need to impress customers, by rapidly pecking out the brand name: TYPE WRITER" (p.333).

However, as Professor Richard Current who had conducted historical research into Sholes and QWERTY (Current, 1988) concluded; "The problem in all this is that we have no specific document, no letter, no note, no patent, no anything which tells us for sure why Sholes did what he did (quoted in Rehr, 1997, p.4, italics in original).

For example, it was widely believed that Sholes had used a list of the most common two-letter sequences in the English language (such as "th" and "er") to then separate as many of these pairs as possible on the typebasket to reduce the problem of adjacent typebars clashing. Gould (1949, p.29), Richards (1964, p.24) and Lundmark (2002, p.17) report this story but provide no evidence for it and Wershler-Henry concludes it is just "speculation" (2005, p.156). As for the alleged deliberate locating of the letters needed to spell "typewriter" in one line, Lundmark (2002, p.19) leaves open whether this was a consequence of accident or design while Gould describes this story as apocryphal (1991, p.68)

In short, while Sholes' problems in developing QWERTY can be clearly identified (jamming and invisibility), whether he found effective solutions to any of the problems he faced is far less obvious. We shall return to this issue in Section 4 after first discussing how QWERTY came to serve as the paradigm case for path dependence.

3. QWERTY and path dependence

What was to become known in some quarters as "the QWERTY problem" had its roots in two landmark papers by David (1985) and Arthur (1989). David's (1985) historical analysis built on Arthur's (1983) modeling of QWERTY-type scenarios to show how specific formats and technologies can become dominant standards. QWERTY provided inspiration for much of the basis for the development of both Arthur and Davids' contributions to what was to become known as path dependence (Arthur, 1994, pp.xvii-xviii), and David (1985) even christened this area of research QWERTY-nomics. The work of Arthur and David differs in method and scope but are complementary in their exploration of mechanisms for possible lock-in to a dominant standard as in the QWERTY case.

David (1985) argues that technical interrelatedness, economies of scale and quasi-irreversibility of investment led to QWERTY becoming locked in as universal keyboard standard. Technical interrelatedness came from the need for system compatibility between the "software" of the touch typing skills and the "hardware" of the keyboard format. Network externalities arising from typists trained in one generally available keyboard format, and in the training market in touch typing led to decreasing cost conditions and scale economies. Quasi-irreversibility resulted from the difficulties any skilled typist would face from unlearning QWERTY-skills if they had to use another format. David's (1985) also cited the potential importance of "historical accidents" in this process and he defined these as "the particular sequencing of choices made close to the beginning of the process" where "essentially random, transient factors are most likely to exert great leverage" (p.335). David argued that through these processes, the QWERTY standard became "locked-in" to its position of dominance, even when it was challenged by the Dvorak design (patented in 1936) which was claimed to be significantly more efficient than QWERTY in terms of ergonomic design and touch typing speed.

As well as finding considerable and rapid acceptance in economic and policy circles (Krugman, 1994, titles a section in his chapter on the economics of QWERTY as "seeing the obvious") these ideas have not passed without controversy. In particular, they have stimulated debate as to whether paths are indeed dependent on random, accidental, chance events; or whether these paths are created through purposiveness, intentionality, agency, and design (Garud and Karnoe, 2001; Garud, Kumaraswamy, and Karnøe, 2010; and Vergne and Durand, 2010). And as was noted in the introduction, Liebowitz and Margolis (1990 and 1995) disputed both the details and the significance of David's (1985) account, including whether Dvorak was indeed the potentially more efficient option.

In the next section we shall look at some recent results which help shed some light on some key aspects of these issues.

4. The role of probability and infrequency in the evolution of QWERTY

Historical methods can be a useful tool to explore and analyse the logic of decisions and actions taken in the distant past, but as the comments by Current above confirm there are severe limits to what these methods have been able to uncover in this context. The lack of reliable contemporary documentation as to what Sholes did and why is perhaps unsurprising given that commercial secrecy would have been an imperative, not just for Sholes but all for those others who had commercial interests in his invention.

Kay (2013a) takes a different route to explore some of the issues (and alleged myths) surrounding Sholes development of QWERTY. The first issue looked at is David's story about the seven letters that made up the word "typewriter" allegedly being put on the top letter line to allow salesmen to show how easy it was to type with this machine. Kay (2013a) asks; what is the probability of this happening by chance? The paper draws by analogy on standard urn selection models in probability theory to estimate the probability of this as:

$$\frac{X\,!(Z-n)!}{(X-n)!Z!}$$

Where X is the number of letters in the top line (10), Z is the number of letters in the alphabet (26) and n is the number of different letters in the word “typewriter” (7).

The probability of this happening by chance was calculated in Kay (2013a) as 0.00018 or about one chance in 5,000. When the same exercise was conducted for the probability that this combination of seven letters could end on any one of the three letter rows by chance, this still turned out to be a highly improbable event. The hypothesis that any such outcome was a random event was therefore discounted and it was concluded that this was consistent with agency or design determining this outcome. Further evidence was cited in Kay (2013a) to support the David (1985) claim that the form this agency or design took was consistent with his salesman story, including this being this being in line with “show-and-tell” sales practices of the time, and also the fact that TYPE WRITER was written in large letters on the front of the Remington typewriter would have served as a useful prompt and guide for users (and indeed salesmen for whom the typewriter was also a novel device) who had difficulties with spelling and/or typing.

The second issue looked at in Kay (2013a) used similar methods and asked; what are the probabilities of frequent letter pairings in written text being separated on the typebasket by chance? Again the paper drew on analogies with common models in probability theory, in this case the probabilities of random seating at a round table leading to a specific couple being seated next to each other. In this case, the probability that each pair for m letter pairs and n typebars (n = 44) would all be split up on the typebasket was calculated as:

$$\left(1 - \frac{(n-2)!\,2}{(n-1)!}\right)^m$$

Kay (2013a) then used a collated list of frequent letter pairs occurring in English text to work out the probabilities of frequently occurring letter pairs being separated on the typebasket by chance with no need for human intervention. It found for even a dozen frequent letter pairs in the English language (i.e. m = 12) that there was a better than even chance that this would happen without Sholes having to intervene and make switches. Increasing the number of frequent letter couples (and m) increased the chances of such an undesirable pairing happening on the typebasket, but the effect was marginal and was quickly running into diminishing marginal returns as m increased and less frequent letter couples were added to the count. But in a further challenge to the “separate frequent pairs” theory, it was found that the alphabetic ABCDEF keyboard, which David (1985, p.333) reports Sholes as starting with, was just as effective as QWERTY in this task. Kay (2013a) concluded that if Sholes did use such a list to separate frequent letter pairs, the probabilities were that it would have been little better than separating letters randomly, and indeed Sholes would have done as well to just stick with the alphabetic format he started with.

So does all this support conclusions that a claim that QWERTY was “scientific” was “probably one of the biggest confidence tricks of all time” (Beeching, 1974, p.40)? The answer is to the contrary, Sholes in fact invented a format that was as near-optimal as could be reasonably be expected, given the state of technical knowledge and user needs that existed in his day.

Sholes’ 44 typebar typebasket meant that numbers and other characters on the typebasket (such as punctuation and fractions) could be relied on to separate some letters from contiguity with others on the typebasket, but with only 44 typebars and 26 letters there would have to be occasions on the typebasket where letters would have to be adjacent to other letters (as Figure 1 shows) What Sholes did was to turn the “separate frequent letter pairs” rule on its head and use another meta-rule; when letters had to be adjacent to other letters on the typebasket, he ensured that these couplings were associated with infrequent letter pairings in English.

This was in fact a simple and elegant rule which was much more effective than trying to separate frequent letter pairs. It can be difficult to work out whether and how frequent a given letter pair is, it is much easier to identify highly infrequent letter pairs. The ad hoc test which can be applied here is; if it is not possible to easily think of many or indeed any words which contain a specific letter pairing (such as QA/AQ) , then make this a candidate for inclusion as part of the contiguous sequence. If you proceed in this way, it is very easy to then construct a long contiguous sequence of infrequent letter pairings.

This can be easily shown in Figure 1. The typebasket has two contiguous sequences;

AQ   SZCDXFVGBHNJ

It is extremely difficult to think of words containing any of the letter pairs on those two sequences, read in either direction (e.g. FV or VF). This is aided by the fact that for many consonants there can a large number of other letters which they rarely, if ever pair up with. For example the 145,000 word "Life on the Mississippi" (hence LotM) by Mark Twain was reputedly the first novel ever typed (Beeching 1974, p. 36), and Kay (2013a) in a search of LotM (Manis, 1999) found that for all possible incidences of letter pairings with B* and *B (where * indicates any consonant), that there were no occurrences for about one-third of all possible consonant pairings for B in the whole of "LotM".

QWERTY on Sholes-Glidden	
Pairing	**Frequency**
AQ/QA	2
SZ/ZS	Zero
ZC/CZ	Zero
CD/DC	9
DX/XD	Zero
XF/FX	Zero
FV/VF	Zero
VG/GV	Zero
GB/BG	2
BH/HB	22
HN/NH	66
NJ/JN	45
Total	146

Table 1: Frequencies for letter pairs in "Life on the Mississippi" PDF
(based on text source: Manis, 1999 and adapted from Kay 2013a, Table 2)

Kay (2013a) then explored the frequency with which letter pairs from the two contiguous sequences occurred in a variety of texts contemporaneous with Sholes. The results for LotM are shown in Table 1 and are remarkable. There were only 146 occurrences of letter pairs in the whole of LotM which were also adjacent on the typebasket. Twain's typist could have typed the whole of the manuscript and encountered failures of Rehr's finger wiggling test only about once every 1000 words.

The infrequency meta-rule has a sub-rule; since vowels have a high propensity to form frequent pairings with other letters, isolate them from other letters on the typebasket. This was achieved by generally buffering the vowels on the typebasket between other characters such as numbers and punctuation. The exception here was QA/AQ, these two options being almost self-evidently infrequent occurrences in the English language.

Further experimentation by Kay (2013a) indicated that the efficiency of the solution could be highly sensitive to just slight perturbations in the basic format. Also, had the Dvorak format been available at the time and substituted for QWERTY on the Sholes/Remington platform it would have breached Rehr's finger wiggling test about 16 times more frequently than QWERTY.

The fact that Sholes's infrequency meta-rule was non-obvious is confirmed by the fact that it has not been publicly articulated for 140 years, but of course once articulated it is extremely obvious and the infrequency meta-rule could easily have been applied to help develop alternative formats. This would have made the need for commercial secrecy a prime concern for Sholes and any collaborators aware of the rule.

The notion of system compatibility (David, 1985; Katz and Shapiro, 1994) is central to understanding the efficiency implications here. David (1985) shows how a major factor in "lock-in" to the QWERTY standard emerging was: "Technical interrelatedness, or the need for system compatibility between keyboard 'hardware' and the 'software' represented by the touch typist's memory of a particular arrangement of the keys" (1985 p.334).

However, Kay (2013a) argued that the relevant complementarities and compatibility issues are best viewed at three levels and not just a single hardware/software level. In these respects there are three key elements of relevance here: format (QWERTY, Dvorak etc.); device (e.g Remington No 7, Underwood No. 5); and user (e.g. whether touch typist or hunt and pecker). In turn, any innovation might solve, mitigate, raise or exacerbate system compatibility issues between any one pair of these three elements; and at any one time, one set of compatibility issues might dominate, at others a combination of compatibility issues might come into play.

QWERTY was explicitly developed to deal with the jamming problem and facilitate format/device compatibility, and these results suggest that what Sholes achieved was about as close to optimal in these respects as could be expected with the technology of his day.

We now turn to what happened next, the description of the differing Remington No.7 and Underwood No.5 technologies facilitated by the author having been able to directly access and experiment with working examples of both.

5. Underwood and the move from up-strike to front-strike technology

Remington's series of models based around the QWERTY format and the up-strike technology helped create the standard for the embryonic typewriter industry in the last quarter of the 19th century (Gould, 1949, p.30). Remington and other typewriter companies made many improvements and innovations to the basic model that Sholes had produced in 1873, the introduction of the Remington No. 7 in 1896 finally solving a significant problem of "blind" typing in that its "new keyboard lock renders it impossible to depress one key after the end of the line has been reached, thus obviating the writing of several characters on one another" (Mares, 1909, .62)

There had been no serious challenges to the growing dominance of Remington and its up-strike technology until Underwood introduced a revolutionary typewriter in 1897, the

Underwood No. 1. After various modifications the Underwood No. 5 was introduced in 1901, a design that was to set the standard for the 20th century typewriter industry (Reinstaller and Holzl, 2009, p. 1010), Underwood itself capturing more than half the global market in typewriters by the 1920s (Beeching, 1974, p.266).

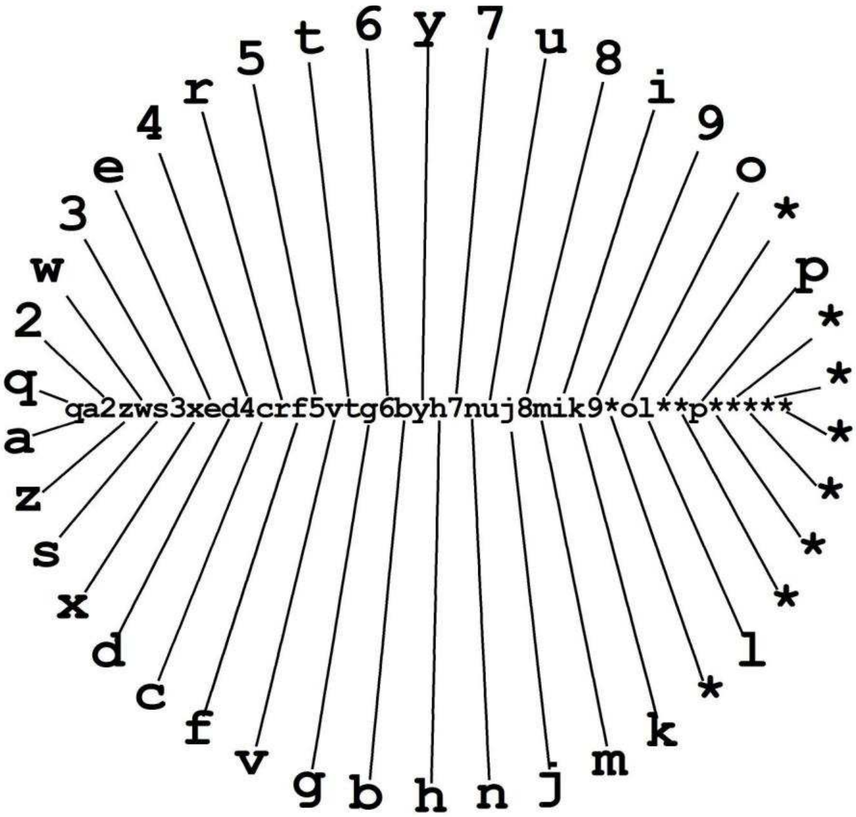

Figure 2(a)The QWERTY 42 character string and its typebasket

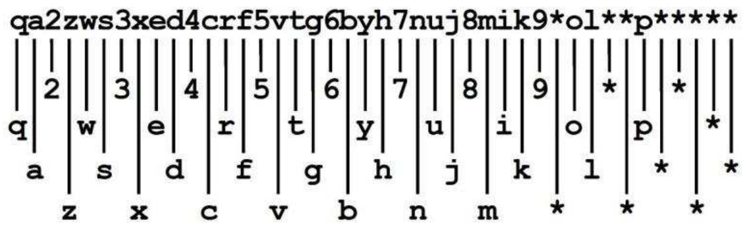

Figure 2(b): The QWERTY keyboard and its 42 character string

Figure 2: The QWERTY keyboard and typebasket on Remington up-strike

The success of Underwood's front-strike innovation was based on enabling typists to see what they typed, as they typed it. This incidentally raises problems for the central role often ascribed to touch typing in the growth of the typewriter industry (e.g. Reinstaller and Holzl, 2009). Experienced touch typists can make mistakes and visibility would be useful for them too, but touch can replace vision in this skill to the extent that touch typists in typing contests in the 1880s were achieving high levels of performance blindfolded (Liebowitz and Margolis, 1990; Campbell-Kelly, 2005) The front-strike innovation and the quicker visual feedback and learning opportunities it afforded would have been of arguably greatest value to novice and poor typists who typically are much more prone to mistakes than touch typists.

But first Underwood had to overcome the same problem that faced all other typewriter manufacturers at the time. It might have a potentially superior technology, but as David (1985, pp.335-336) explains, by the mid-1890s QWERTY had become “locked-in” as universal standard through the combination of technical interrelatedness, economies of scale and quasi-irreversibility of investment described above in Section 3. Faced with this reality, Underwood adopted the QWERTY format in its up-strike models. Not only did this decision facilitate the adoption of its products in the market place, any other decision stood the risk of killing its promising innovation stone dead at birth.

However, this decision in turn had important efficiency implications for format/device compatibility, which was the major source of competitive advantage for Sholes’s earlier invention. To understand the efficiency implications of Underwood’s decision, we need to first analyse the format/device relations underlying Sholes’s invention and how these had translated into such a high degree of format/device compatibility.

Figure 2 shows a stylised version of keyboard and typebasket relationships in the Remington No. 7 Model. There had been some modifications from the 1873 version, C and X had been switched and M dropped to the bottom row. If the letters on the four keyboard rows are read from left to right, this results in the 42 character string or code shown at the top of Figure 2(b), with asterisks indicating a character other than letter or number:

QA2ZWS3XED4CRF5VTG6BYH7NUJ8MIK9*OL**P*****

This is the same code that still lies at the heart of the universal standard for keyboards today, allowing for national customization (the corresponding character strings that generate many other variants such as the German QWERTZ and French AZERTY tend to share much of their DNA with QWERTY). If you are reading this on a standard US or UK English PC (or are near one), look at the letter Q on row 2. The character immediately to the right of Q is A on row 3. Then the character immediately to the right of A is the number 2 on row 1. And the character immediately to the right of 2 is Z on row 4. After that the sequence repeats itself, row 2, row 3, row 1 row 4 … and so on for all 42 characters. That is the core of the modern English keyboard, the only difference in the string being that the number 0 has replaced the * after L on the string above.

The Remington No 7 then used the Sholes protocol to translate this 42-character code from the keyboard onto the typebars on the circular typebasket. This is also shown in stylized fashion in Figure 2(a) which shows how the 42 character string is distributed around the circular typebasket using a protocol which separated the characters in alternating fashion, rather like a zip being opened up. This unzipping peeled the 21 characters from the top two rows of the keyboard off to the top half of the typebasket; while the 21 characters from the bottom two rows of the keyboard were peeled off to the bottom half of the typebasket

The introduction of a shift key in later Remington models such as the No. 7 allowed the number of typebars to be reduced to only 42, the price of which was more letter pairings on the typebasket. There was now only one (but longer) contiguous letter sequence on the typebasket in Figure 2:

QAZSXDCFVGBHNJMK

In principle, A and S are two of the letters that should be prevented from being contiguous with any other letters on the typebasket given their prevalence in frequent letter pairs (Kay, 2013a, Table 1), and at first sight their appearance in the contiguous sequence looks highly risky in these respects. In practice, if you must to do this then one of the safest stratagems is to sandwich them between Q, Z and X, three of the most infrequent letters in the English language. We shall look at the evidence on this when we compare and contrast this with the Underwood solution.

We can now turn to the potential implications for the Underwood front-strike innovation of its adoption of the QWERTY format. This is shown, again in stylized fashion, in Figure 3. It is important to note that the Underwood QWERTY keyboard and the 42 character code that it generated is exactly the same as in the Remington No 7.

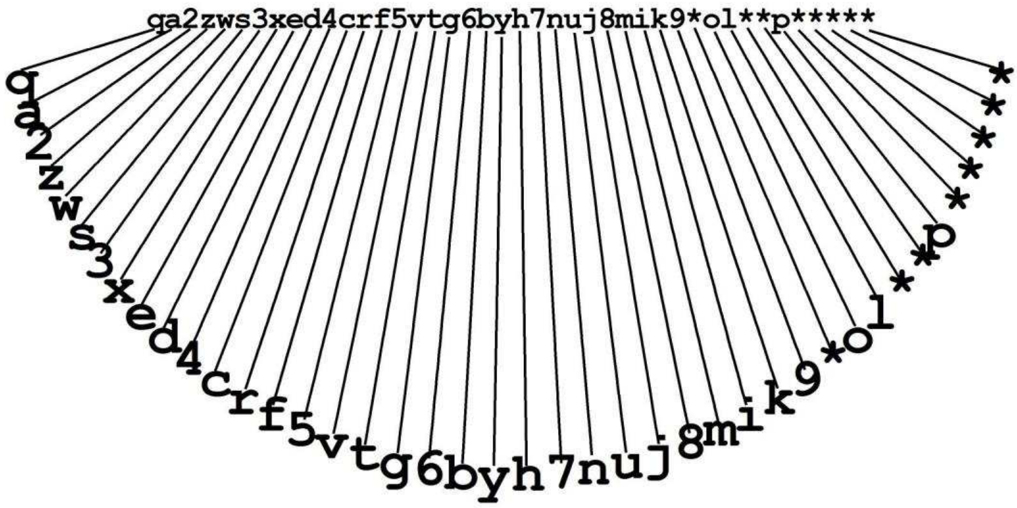

Figure 3(a):The QWERTY 42 character string and its typebasket

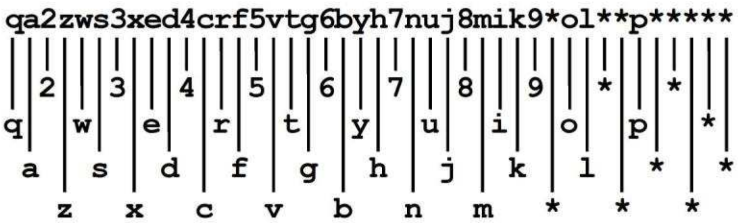

Figure 3(b): The QWERTY keyboard and its 42 character string

Figure 3: The QWERTY keyboard and typebasket on Underwood front-strike

What the Underwood front-strike technology did was to move from the Remington circular typebasket to a single arc over which the typist could see the results of their typing without having to lift the paper carriage as in the Remington up-strike technology. The problem was that Sholes and Remington explicitly designed for compatibility of QWERTY format with its circular typebasket. So how did Underwood deal with this issue and what were the implications?

Perhaps the easiest way to understand what Underwood did is to think of the 42 characters of the Remington typebasket written around the rim of a paper plate. Now imagine the top half of that plate folded into the bottom half, so bringing the two halves together. The effect is that characters which were formerly separated from each other in opposing hemispheres are now brought into direct contact with each other. That is in effect what the Underwood integration of QWERTY with its front-strike technology did. The results can be seen on its typebasket in Figure 3, perhaps the most immediately obvious effects being that the vowels E, I, O and U are now brought into contiguity with other letters, and also that instead of one long contiguous sequence of letters as in the Remington No 7 we now have a series of short contiguous letter sequences:

QA ZWS XED CRF VTG BYH NUJ MIK OL

What letter pairings on the printed page can be formed from pairs on these contiguous sequences? The results are shown in Table 2, along with the results for the Remington 7 for comparison purposes, again using LotM for demonstration purposes

QWERTY on up-strike		**QWERTY on front-strike**	
Pairing	**Frequency**	**Pairing**	**Frequency**
QA/AQ	2	QA/AQ	2
AZ/ZA	73	ZW/WZ	0
ZS/SZ	0	WS/SW	410
SX/XS	1	XE/EX	723
XD/DX	0	ED/DE	8765
DC/CD	9	CR/RC	955
CF/FC	0	RF/FR	1159
FV/VF	0	VT/TV	0
VG/GV	0	TG/GT	46
GB/BG	2	BY/YB	943
BH/HB	22	YH/HY	134
HN/NH	66	NU/UN	2405
NJ/JN	45	UJ/JU	313
JM/MJ	2	MI/IM	3617
MK/KM	14	IK/KI	787
-	-	OL/LO	3821
Total	236	**Total**	24,080

Table 2: QWERTY on Remington up-strike vs. QWERTY on Underwood front-strike

Table 2 shows that a price of reducing the number of typebars on Remington No. 7 compared to early Remingtons was to increase the incidence of letters which were adjacent on the typebasket and which were also paired on the printed text of LotM from 146 such events to 236.

However, this pales into insignificance compared to the explosion in such events using the Underwood No. 5 to 24,080. While these events would be encountered about once every 600 words in LotM using the Remington No. 7, they would be encountered about once every 6 words using the Underwood No. 5. Under Sholes and Remington, the QWERTY keyboard and up-strike typebasket had co-evolved as an integrated system which maintained a high degree of format/device compatibility. What the Underwood front-strike innovation did was to create a hybrid and graft a QWERTY "head" on to a typebasket "body" for which QWERTY was simply not designed.

So how did the front-strike Underwood conversion of the up-strike typebasket manage to avoid the jamming problem associated with Rehr's finger-wiggling test? The simple answer is it did not, on the contrary the price of increased device/user compatibility in the form of print visibility on front-strike machines was the reintroduction of major format/device compatibility problems that Sholes' up-strike QWERTY had largely solved. There were numerous patents which tried to reduce the jamming problems that front-strike had introduced, but which would not be solved until the IBM Selectric in 1961. Margolis (2013) cites four such patents from 1927 to 1952 (at least two of which note that jamming could be a frequent problem), but there were many more, some of which made clear that the problem lay particularly with proximate or particularly <u>adjacent</u> typebars on the typebasket (and implied failures of Rehr's finger-wiggling test). As early as 1906 one patent was already highlighting how front-strike technology had brought back the contiguity problem that Sholes had largely solved;

> "Type-bars, especially in front strike machines, are often closely arranged, so that in rapid operation there is liability of clashing" (US patent 811,182, filed by B. C, Stickney)

But despite significant inventive effort to solve this problem, some decades later a 1948 patent still noted;

> "When a typewriter is used, and <u>especially when used by other than highly skilled operators</u>, it frequently happens that two <u>adjacent</u> keys will be depressed at the same time, thereby elevating two type bars simultaneously and causing the outer or distal ends of the type bars to bind together or jam adjacent the ribbon guide" (US Patent 2,529, 604, filed by W. A. Gooch, italics added).

And a 1950 patent also noted that

> "a type bar may be in process of a rebound, particularly in the center of the typebasket, while an <u>adjacent</u> one is in the initial stage of operation and the two sometimes collide and cause a jamming of the mechanism" (US patent 2,651,349, filed by H. J. Kistiier, italics added)

The Underwood No. 5 front-strike technology was developed to deal with the invisibility problem and facilitate device/user compatibility and was visibly (in more than one sense) successful in that effort. But since QWERTY was custom-designed for format/device compatibility in Remington's up-strike technology, a price of adopting QWERTY in Underwood's front-strike technology was that all the hard-won gains in format/device compatibility that Sholes had strived for with QWERTY were lost.

We shall review the implications of this more fully later, but first we shall look at the potential efficiency implications for what was once heralded as a serious challenger to QWERTY, the Dvorak or DSK (Dvorak Simplified Keyboard) format.

6. The efficiency implications of Dvorak

The Dvorak or DSK (Dvorak Simplified Design) design was patented in 1936 and was claimed on the basis of experiments and speed tests to enable faster typing than QWERTY (David, 1985). For our purposes here, we just summarise that it has been claimed that the

Dvorak format does indeed have superior format/user compatibility but that these claims have been contested (e.g. Liebowitz and Margolis 1990 and 1995). However, there are other potential efficiency implications that follow from our analysis above which we turn to here.

First, it can be misleading to just characterise Dvorak as simply a competing format to QWERTY. Dvorak's very existence depended on QWERTY winning the late 19th century format standard war. As Kay (2013a) notes, in those days QWERTY on its Remington platform was competing in a selection environment that was a mechanical version of the Cambrian explosion with its proliferation of biological body plans. Just as in the Cambrian explosion, the explosion in market demand for typewriting machines in the late 19th century led to a proliferation of mechanical body plans in which keyboard rows could multiply or even be replaced by arcs. QWERTY was not just a specific ordering of letters, its full legacy as embodied in the Remington No.7 was a 42-character code distributed on four rows of 10, 11, 11 and 10 characters respectively, top row numbers, bottom three row letters, characters spacing from left to right on the keyboard in the order row 2: row 3: row 1: row 4 (recurring). Underwood had dealt with the QWERTY lock-in problem by not fighting it at all and simply adopting the complete QWERTY package. But even though Dvorak offered an apparently radical solution by rearranging the order of characters in the 42-character QWERTY code, in all other respects it was in reality a highly conservative solution which preserved all the core parameters of the QWERTY body plan.

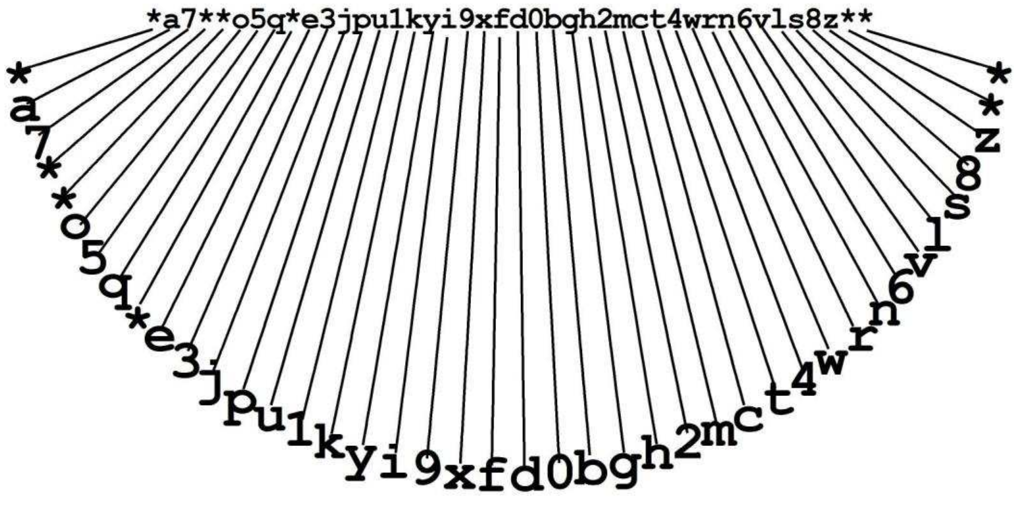

Figure 4(a)The Dvorak 42 character string and its typebasket

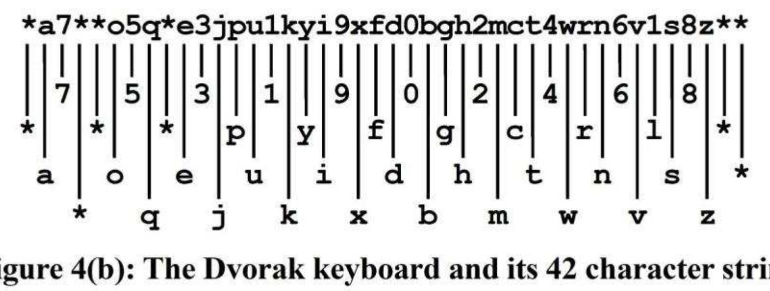

Figure 4(b): The Dvorak keyboard and its 42 character string

Figure 4: The Dvorak keyboard and typebasket on Underwood front-strike

So bearing in mind that Dvorak was designed with enhanced format/user compatibility as its objective, what, if any implications did it have for format/device compatibility? First, Dvorak's own 42-character code transplanted onto a QWERTY keyboard is:

*A7**O5Q*E3JPU1KYI9XFD0BGH2MCT4WRN6VLS8Z**

And the resulting contiguous letters on the Underwood up-strike typebasket are:

JPU KYI XFD BGH MCT WRN VLS

Table 3 looks at how QWERTY and Dvorak compare in terms of the incidence of letter pairings on the typebasket also leading to letter pairings on the printed page, and again we use LotM as demonstration case

QWERTY on front-strike		**Dvorak on front-strike**	
Pairing	**Frequency**	**Pairing**	**Frequency**
QA/AQ	2	JP/PJ	0
ZW/WZ	0	PU/UP	2215
WS/SW	410	KY/YK	54
XE/EX	723	YI/IY	181
ED/DE	8765	XF/FX	0
CR/RC	955	FD.DF	26
RF/FR	1159	BG/GB	2
VT/TV	0	GH/HG	1675
TG/GT	46	MC/CM	2
BY/YB	943	CT/TC	1446
YH/HY	134	WR/RW	188
NU/UN	2405	RN/NR	822
UJ/JU	313	VL/LV	158
MI/IM	3617	LS/SL	890
IK/KI	787	-	-
OL/LO	3821	-	-
Total	24,080	**Total**	7,659

Table 3: QWERTY on Underwood front-strike vs. Dvorak on Underwood front-strike

The results are very interesting, Dvorak would have encountered less than a third of the incidence of letter pairs in LotM which were also adjacent on the type basket compared to QWERTY (7,659 compared to 24,080). The claims made for Dvorak generally revolve around its alleged superiority over QWERTY in terms of format/user compatibility. But the test results in Table 3 indicate that Dvorak would appear to have a clear advantage over QWERTY on format/device compatibility grounds alone.

How did Dvorak manage to put such clear blue water between itself and QWERTY in these terms, and was this a consequence of accident or design? The main reasons for Dvorak's advantages in this context can be seen by first comparing QWERTY on up-strike and front-strike typebaskets. As long as QWERTY was carried on the Remington up-strike platform, row 2 on the keyboard was generally the safest place to put vowels in terms of format/device compatibility because the Sholes protocol then tended to buffer them between numbers and punctuation on the upper hemisphere of the typebasket.

However, to use our paper plate analogy, folding the two hemisphere of the up-strike typebasket together to form the front-strike typebasket destroys that advantage. Indeed from being the safest place for vowels in terms of format/device compatibility, row 2 is now the worst. Where before on the up-strike typebasket the vowels were buffered between numbers and punctuation from row 1 on the keyboard, now the front-strike typebasket buffers characters from row 2 between characters from rows 3 and 4 of the keyboard. And since these two rows are of course heavily populated by letters, this helps explain why QWERTY prima facie performs so badly in terms of format/device compatibility on the front-strike technology in Table 2.

But Dvorak avoids much of the dangers posed by vowels in this context by shunting them to the left of the keyboard in Figure 4(b) and (mostly) buffering them on the typebasket in 4(a) with numbers and punctuation from rows 1 and 2. There are echoes here of Sholes infrequency solution for QWERTY in which a sub-rule was to isolate vowels on the typebasket from contiguity with any other letters.

So did this happy solution occur by accident or did Dvorak do this deliberately? We do not know but there is one thing that that can be said with certainty. If Dvorak did deliberately apply an "isolate vowels" rule for at least part of his design with format/device compatibility in mind, then like Sholes he would have had every incentive to keep quiet about it because here also, once articulated, the rule (and any potential source of competitive advantage) could be applied to keyboards generally and not just Dvorak's own design.

7. Since Dvorak was invented

The last section suggests Dvorak potentially had a clear advantage over QWERTY in terms of format/device compatibility considerations in addition to a publicly claimed (though contested) possible advantage in terms of format/user compatibility. However this was not a static environment.

First, even if Dvorak had been given sufficient testing and market exposure to validate any gains it may have offered in terms of format device compatibility, by the 1960s the IBM Selectric was eliminating the jamming problem and in turn any advantage that Dvorak might have had over QWERTY in terms of format/device compatibility (Margolis 2013) .

Second, as far as format/user compatibility is concerned, Dvorak was invented in an era when typing was largely a specialised task often carried out in typing pools dedicated to the activity. Any increase in typing speed there would directly translate into an increase in labour (typist) productivity of comparable magnitude. But the institution of the typing pool sank into decline from the 1970s (Nakamura, 2004) and has now largely gone, while the art of ten-finger touch typing (which Dvorak was designed for) is by some accounts also now a dying art (Johnson, 2003). Today those who type (including but not exclusively secretaries) typically also have many administrative and managerial tasks other than typing. Even if Dvorak could increase productivity in the specific task of typing, its impact is diffused and diminished to the extent that this is now only one of many elements in labour productivity. But of course the pain of retraining would still be a fixed cost borne by all who undertook it

Thirdly, other technological developments and needs in recent years such as text inputting in hand-held devices raise device/user compatibility issues which positively conflict with Dvorak's rationale based around ten finger touch typing. Given that it is impractical to miniaturise fingers to match miniaturisation of devices, in this context at least Dvorak can face device/user compatibility problems that it was simply not designed to cope with.

In short, if Dvorak did possess any potential efficiency advantages over QWERTY in 1936, the evidence is that these advantages have either been eliminated or dissipated over the intervening years.

In the next section we shall discuss the potential implications of our analysis here and in the previous sections for the literature on increasing returns and path dependence

8: Discussion

At this point we can review a number of arguments and claims that have been made in the literature regarding the economics of QWERTY.

8.1: Did QWERTY lack any scientific basis and was it simply a "confidence trick"?

This argument was put forward by Beeching, who argued that describing QWERTY as "scientific" was "probably one of the biggest confidence tricks of all time" (1974, p.40, see also Wershler-Henry, 2005, p.153). Gould (1949) had earlier attributed the widespread subsequent acceptance of QWERTY "simply to the fact that it was first in the field – not at all to its own merits" (pp.28-29). We can quickly reject those arguments, the evidence is that QWERTY was a solution based on a solid chain of reasoning and deduction by Sholes resulting in a remarkably high degree of format/device compatibility.

8.2: Was QWERTY a consequence of historical accidents and/or random factors?

David characterised the early history of QWERTY competing against "rival keyboard arrangements …likely to be governed by 'historical accidents'" where "essentially random, transient factors (were) most likely to exert great leverage" (David, 1985, p. 333). While not denying that accidents and chance can play important roles in historical events, our conclusion that the genesis of QWERTY was a consequence of genuine intellectual endeavour is difficult to reconcile with such a view. Instead it appears more consistent with the notion discussed in Section 3 above that history is created through agency and design (Garud and Karnoe, 2001; Garud, Kumaraswamy, and Karnøe, 2010; and Vergne and Durand, 2010).

Arthur (1988) does offer an important caveat; just because an observer may describe an event as random does not mean they necessarily believe it is undirected and lacking agency, this just may appear so because of the "limited discerning power" of the observer (p.118). This does offer at least some scope for reconciling what appears at first sight to be conflicting views of history. But it should be noted that if and where such reconciliation is possible (as may be the case with QWERTY), then it is asymmetric in so far as the net effect will be to further enhance recognition of the important role that agency and design can play, and further diminish the potential role for accidents and chance.

8.3: Is QWERTY an "inferior" standard?

This is a claim that has been made repeatedly since David (1985) and as we noted in the beginning of this paper the notion that QWERTY was an "inferior" standard has become crystallised in Krugman and Wells' (2006) definition of "the QWERTY problem". But "inferiority" is a relative concept based on what alternatives are actually available at a given time, and any claims that QWERTY was inferior has to specify "inferior" relative to what, when, and for whom, otherwise the label is meaningless.

Based on the analysis here and the wider literature, the strongest available evidence to support any claim that QWERTY was "inferior" to any other standard would appear to hold relative to Dvorak in terms of format/device compatibility and (possibly) format/user compatibility following Dvorak's invention in 1936. But the context was a period when typing still tended to be a dedicated specialised task often carried out in typing pools. It is difficult to sustain an argument that QWERTY was an inferior standard prior to 1936, given the absence of any standard that had been found superior to QWERTY on the basis of generally agreed efficiency criteria. And as we saw in section 7, if Dvorak did possess any potential efficiency advantages over QWERTY in 1936, the evidence is that these advantages have either disappeared or been largely dissipated over the subsequent years. Any argument that Dvorak was superior to QWERTY is highly time- and context-specific and has been rendered obsolete by the passage of time, the evolution of technology, and changes in work practices. Any blanket assertion that QWERTY was (or is) an inferior standard has to be supported with credible evidence as to on what basis it was (or is) to be judged inferior, and certainly the standard witness for the prosecution of any such case (Dvorak) lacks credibility.

8.4: Were typewriter standards prematurely standardized around the wrong system"?

David (1985) argues that typewriter standards were driven "prematurely into standardization on the wrong system" represented by QWERTY (p. 336, italics in the original). However as we have noted above, a corollary of ascribing inferiority to any system is that we have to identify some superior system, and if QWERTY was the "wrong" system, it raises the question as to what was the "right" system. Suppose we grant Dvorak a time-limited and context-specific superiority over QWERTY. Should standardisation have been deferred until Dvorak was invented some 63 years after QWERTY, and then Dvorak made industry standard? In that case the price would have been the sacrifice of network externalities and economies of scale that standardisation around QWERTY would have generated, plus the costs of moving to a new standard, in exchange for any questionable and temporary productivity gains that Dvorak would have provided.

The reality of course is that if standardisation around QWERTY had somehow been prevented, there would have been little incentive to invent Dvorak in the first place. QWERTY was the progenitor of Dvorak, its relationship to Dvorak was more that of a parent than that of a sibling. As we noted in Section 6, QWERTY was not just a rival keyboard to Dvorak, Dvorak needed the QWERTY body plan to have succeeded and become industry standard in order to have any commercial rationale itself. Consequently, any argument that QWERTY should have been somehow inhibited from becoming that dominant standard in order to create opportunity for Dvorak is self-refuting.

Standardisation was in fact a consequence of QWERTY being the right system at the right time. Oden (1917) in discussing the role of Remington in the evolution of the typewriter after 1882 concluded;

> "The next step necessary in the evolution of the typewriter was the education of the public to its commercial value. This was no small undertaking because of custom and prejudice. A typewritten letter often offended the recipient, who seemed to feel that it was a reflection upon his intelligence and ability to read pen writing. For a number of years the typewriter was looked upon as a luxury used only by those who had sufficient money to satisfy a whim; later it became a convenience, and finally an absolute necessity" (p.23).

This shows the important role that Remington and QWERTY played in establishing what Margolis (2013) calls the "proof of concept" for the typewriter. Part of that process was persuading novice typists that it would be worth expending the effort (and possibly money) needed to acquire these strange new skills. While Remington's marketing and educational effort certainly provided valuable externalities for others in this emerging industry, if Remington had not hoped to internalise much of the benefits from this effort, they would have had no incentive to do it in the first place. Becoming dominant standard was in a sense a by-product of this internalisation drive. But if the product had not been so well designed by Sholes in the first place and if the machine kept jamming, Remington could not only have lost out to some fitter rival in the battle of the standards, development of this novel new industry could have been impeded or delayed. Standardisation did not happen when it did despite QWERTY being inefficient, it happened when it did because QWERTY was efficient, a feature which actively promoted the growth and diffusion of this nascent innovation and infant industry.

8.5: Does QWERTY provide justification for government intervention in helping create or change standards?

As noted in our introduction, Krugman and Wells (2006) see government as playing a useful role both in helping a establish an industry standard and to help it avoid getting trapped in what they describe as the QWERTY problem (pp. 534 and 536).

The problem here is that just as "inferior" has to be specified with respect to what, when and for whom, so any justification for government intervention has to be specified with respect to why, when, and for whose benefit? How could or should government have intervened when QWERTY was busy establishing "proof of concept" for the typewriter innovation through the simple expedient of just being the most efficient game in town? Should it have intervened to direct or induce system-wide switches to Dvorak after 1936 only for regret when any notional gains from such switches soon disappeared or greatly diminished? It could be argued that government could not be expected to anticipate the changes in technology, work practices and products that would erode or eliminate any notional competitive advantage that Dvorak might have enjoyed over QWERTY. But that is perhaps the whole point. Even with hindsight it is difficult to see what interventionist role government could or should have played here in either setting or changing standards – and governments, as with individuals, are much better at hindsight than foresight.

Obviously these results and comments relate to QWERTY, but its role as paradigm case for the possible role of government in setting and changing technological standards may give them resonance beyond this particular case.

However, there could have been scope in here for government intervention other than in standard setting. Mares (1909) quotes (from newspaper sources of 1903) one executive whose company was a member of the "Typewriter Trust" and whose members included the leading up-strike typewriter companies of the day (including Remington) and that "by means of the combine prices have been kept at a high level for thirteen years." (p. 287). Clearly this would seem to have been a prima facie case for government intervention in anti-trust terms if not in standard setting. However, the Trust arguably failed to achieve its aims. Underwood, which was not a member of the Trust, quickly broke through into market acceptance with its front strike technology which then set the standard for 20th century typewriters.

8.6: Does QWERTY provide support for the existence of path dependence in the evolution of a technological standard?

David (1985, p.332) cites QWERTY as an example of a path dependent process. However Vergne (2013) notes that path dependence refers to the contingent selection of a stable equilibrium in a sequential stochastic process. It follows that if path-dependent sequences could be rerun multiple times they would not always converge to the same equilibrium outcome.

Clearly path dependence itself can be contingent and depend on how and over what time period the events in question are specified. For example Kay (2013a) notes that if Sholes out riding his bike pre-QWERTY had been distracted by a butterfly flapping its wings and rode over a cliff, then we might have no QWERTY at all, and instead we might be staring at keyboards with a very different body plan and format. Also, Reinstaller and Holzl (2009) in a highly detailed case account argue that small events and contingencies of history can be identified as instrumental in the evolution of QWERTY, consistent with path dependence.

But path dependence related to QWERTY has generally been cited in the context of the contingent selection of a supposedly inferior standard (QWERTY) through historical accident, and at the expense of a supposedly superior standard (such as Dvorak). The results here extend those of Kay (2013a) and help support an argument that in a QWERTY/Dvorak battle, there is no path with Dvorak on it which would have led to its eventual adoption as the dominant standard, even if Dvorak was granted free choice over time of entry into the standards battle. Any format/user and/or device/user compatibility advantages that Dvorak may have had were contingent on the QWERTY body plan having first won the standards battle, by which time it would have been too late for Dvorak; but if Dvorak challenged QWERTY at its inception or during the early days of up-strike technology it would have been easily out-competed by QWERTY on format/device compatibility grounds alone. As Vergne (2013) notes, the argument in Kay (2013a) that QWERTY would always win any replays of the tape of history against Dvorak means that QWERTY cannot be explained by path dependence. QWERTY did not win by accident, it won by design.

9. Conclusions

There are several conclusions which follow from our analysis. QWERTY was not an accident of history; it was not unscientific or inferior, it was instead a carefully designed and highly efficient innovation. The analysis here leaves no clear justification for any government role in setting or changing standards, even with the benefit of hindsight. Despite its central role in the literature on path dependence, the narrative here is not consistent with QWERTY itself being a path dependent phenomenon. And despite its role as "paradigm case" for what Krugman and Wells (2006) describe as "the QWERTY problem", QWERTY itself cannot be taken as an example of that problem, nor justification for policy prescription based on common current perceptions as to what constitutes that problem.

At the same time, the analysis is not just consistent with notions of network externalities, increasing returns and lock-in (Arthur, 1983 and 1989; David 1985), it is crucially dependent on these influences to help explain the process by which QWERTY became universal keyboard standard. In these respects it is also consistent with Page (2006) who shows that increasing returns are neither necessary nor sufficient for historical dependence. Hopefully such separating out of path dependence from increasing returns at both conceptual and empirical levels will assist future analysis, both here and in other areas of research

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