Causes of Path Dependence

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In a giraffe's neck, the recurrent laryngeal nerve passes signals from the brain to the larynx just under its mouth. This nerve takes a counterintuitive path: all the way down the giraffe's 6 feet of neck and further, around the aortic arch in the heart, and back up the neck to its destination (fig. 1). This detour doesn't do the giraffe any favors. Long nerves take more time to pass signals and can be damaged at any point along their length.

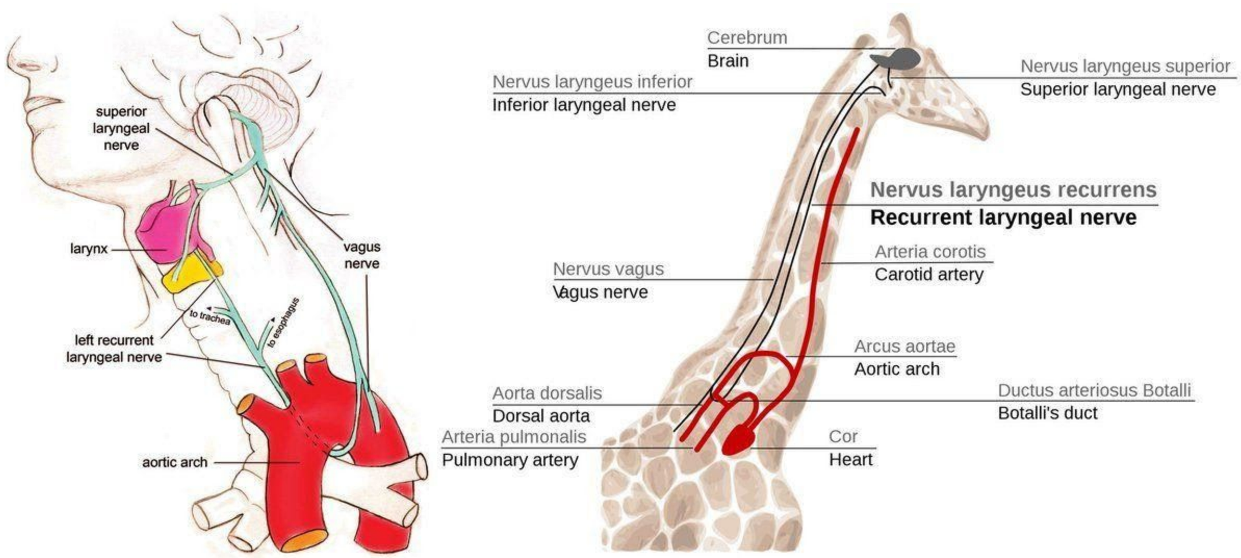

Figure 1. Human vs giraffe recurrent laryngeal nerve (Medeyko, 2010).

This kind of thing is to be expected from natural selection. The common ancestor of all land vertebrates was a fish without a neck to speak of, so the nerve's path was of little consequence. As longer necks became selected for, no guiding hand could reach in and move the nerve to a more direct path from the brain to the voice box. Mutations may have done this, but with adverse effects that outweighed the benefits. The result was a gradual lengthening of the nerve to the detriment of long-necked animals (Dawkins, 2009).

The initial looping around the aorta was at first innocuous, but it led into an evolutionary trap for the giraffe. The nerve's lengthening was an outcome due solely to the irreversibility of a previous outcome. Economists call this phenomenon *path dependence* (David, 1985).

In nature, path-dependent phenomena are commonplace because no intentional effort is exerted to avoid or escape such traps. Society is different, governed by intention, foresight and a freedom to make large corrective leaps if deemed necessary. Conscious decision is a more powerful force for change than random mutation, and the free market is a more powerful selective force than natural selection. Why, then, do societies still fall into these traps?

Systemic cultural shifts are daunting, even when urgently necessary. Chief among these is the fight against climate change. The effort required to curb its effects will be immense in scope and require the participation of many disciplines. Strong action on climate change is globally favored (Pew Research, 2019), but many are left with a sense that even immense personal sacrifice will make no perceptible difference. So their lives continue as normal save some pent-up anxiety.

Study of cases like this shows that path dependence arises naturally in the free market, and that communication and long-term thinking are necessary in overcoming it.

Literature Review

Economist Paul David coined the term *path dependence* in a discussion of the QWERTY keyboard layout's success over the alternative DVORAK Simplified Keyboard. As he defines it, "A path-dependent sequence of economic changes is one of which important influences upon the eventual outcome can be exerted by temporally remote events, including happenings dominated by chance elements rather than systematic forces" (David, 1985). He concludes that QWERTY is a market failure due to path dependence, specifically that "touch typing gave rise to three features of the evolving production system which were crucially important in causing QWERTY to become 'locked in' as the dominant keyboard arrangement. These features were *technical interrelatedness*, *economies of scale*, and *quasi-irreversibility* of investment" (David, 1985).

Five years later, economists Stan Liebowitz and Stephen Margolis called David's premise into question: "We show that David's version of the history of the market's rejection of Dvorak does not report the true history, and we present evidence that the continued use of QWERTY is efficient given the current understanding of keyboard design" (Liebowitz & Margolis, 1990). Liebowitz and Margolis go further in a subsequent paper: "Although it is fairly easy to identify allocations, technologies, or institutions that are path dependent in some form, it is very difficult to establish the theoretical case or empirical grounding for path-dependent inefficiency." To qualify this claim, they distinguish three strengths of path dependence (Liebowitz & Margolis, 1995):

> *First-degree path dependence* is the mere assertion that historical decisions can affect later decisions. A situation is first-degree path dependent if some decision in the

past affects the costs of current choices so that a switch "off of the current path" is more costly than "staying on the path."

Second-degree path dependence requires that the current path is less beneficial than an alternate path, but that this was unknowable at the time the decision was made. Regrettable decisions are possible to make with purely rational behavior but imperfect information, and this degree of path dependence captures that notion.

Third-degree path dependence further stipulates that the decision is *remediable*. Liebowitz & Margolis say this means that "there exists or existed some feasible arrangement for recognizing and achieving a preferred outcome," but that due to sensitive dependence on initial conditions a less beneficial outcome was chosen.

Liebowitz and Margolis contend that third-degree path dependence is the only kind that could cause market failure, and that the theoretical and empirical support for its existence is flimsy. The core of their argument is that in the case of a path-dependent market failure: "We would have to ask why no arrangement was made to bring about consideration of all costs and benefits. If our only answer were that such arrangements are too costly ... then we would not really have a feasible alternative allocation. Since the costs of making these arrangements are not different from any other costs, we would conclude that the costs of switching formats exceed the benefits" (Liebowitz & Margolis, 1995).

David responds to this with derision. He accuses Liebowitz, Margolis and other critics of circular logic, calling their argument "tantamount to saying that market failure cannot happen, because if it did happen, markets would work to correct it" (David, 1999).

This exchange is the center of a larger discussion of path dependence. Inspired by David's original paper, economists such as Paul Krugman have made QWERTY vs Dvorak the prototypical example of path dependence. Vergne and Durand have recently attempted to reconcile the opposing viewpoints by more formally defining path dependence and shifting focus toward modeling due to the low verifiability of empirical cases of path dependence (Vergne & Durand, 2010).

The Dvorak Keyboard

David, Liebowitz and Margolis examined the history of the typewriter and of the QWERTY and Dvorak layouts. Recent perceptions of Dvorak, however, have been comparatively neglected.

Some who try Dvorak document their experiences on YouTube or in blogs. Reviews are mixed. Tech reviewer Wolfgang says "I wouldn't say that typing in Dvorak is noticeably faster than typing QWERTY, however it's definitely more comfortable. ... Would I recommend Dvorak to anyone? No, definitely not. It might be better than QWERTY, but it's not that much better, especially considering the disadvantages, for example keyboard shortcuts" (Wolfgang, 2019). After the relearning process, Wolfgang still uses Dvorak, despite his recommendation that others do not make the switch.

The Dvorak community today intersects strongly with the Linux community. Linux is viewed as an alternative operating system in the same way that Dvorak is an alternative keyboard. It is often voluntarily installed onto hardware, replacing a different default OS. Linux attracts people who are interested in exploring alternative lifestyles. Sometimes their goal is to improve their productivity or user experience, but other times it is more of a personal fascination with taking the road less traveled or a ploy for social status. The term "Linux hipster" is used by the community to refer to those who have this mindset. Linux & Open-Source commentators Level1Linux have said “It’s a battle for esoteria—not because necessarily you like esoteric things or you have you know superior taste but it’s because it is a competition, and that's why I'm calling a lot of the Linux users on the Internet internet hipsters” (Level1Linux, 2015).

Dvorak fulfills a similar niche today. Software engineer Patrick Brown describes why he was first drawn to Dvorak: “Early in my career I thought optimizing every portion of my interaction with my code would make me a better engineer. I used a crazy Awesome WM setup on Arch Linux. My Vim and ZSH were 256 color beauties with power-lines and git integrations. I spent hours configuring these. A part of my blind optimization was switching to Dvorak” (Brown, 2017). Five years later, he switched back to QWERTY after struggling to support all the features he needed on the Dvorak layout. He says, “While there are many data points that imply that Dvorak is a superior layout, ultimately, we must settle on a common format. If we tried to optimize every standard we had, we’d all being [*sic*] using different number systems, speaking different languages, and probably typing on a Colemak keyboard (if I’m honest). Yet we don’t, because there are harder problems to solve and these tools allow us to collaborate with each other on said problems” (Brown, 2017).

In other words, trying to optimize a standard past a certain point leads to a proliferation of standards, and a fragmentation of users across each, a situation worse than a single inferior standard. The “Colemak keyboard” mentioned is one of many further refinements on Dvorak, each with its own fringe set of users who believe it to be better. This splintering could be why Dvorak (or any alternative to a standard in a similar position) can no longer gain a critical mass of support and replace QWERTY.

The Jankó Keyboard

The case of the Dvorak keyboard has an odd parallel in the music world. Hungarian pianist and engineer Paul von Jankó patented an alternative to the traditional piano layout in 1882. His insight was to eliminate the “missing” black keys between some white keys and instead simply alternate black/white/black/white down the whole length of the keyboard (fig. 2). The extra rows of keys play the same notes as the lowest two rows, affording more ergonomic alternate fingerings. Jankó’s layout boasts two practical advantages over the traditional layout:

Figure 2. Piano with the Jankó layout (JankoPiano, 2014).

1. Every key has the same fingering, so transposing from one key to another only requires sliding to a different part of the keyboard, without changing the shape of any chord or scale.

2. The keys are more compact due to the removed gaps, allowing players to reach larger intervals with one hand.

In Jankó's time, the keyboard received some glowing reviews. Piano builder Alfred Dolge said in a 1911 retrospective: "Entirely new music can be written by composers, containing chords, runs and arpeggios, utterly impossible to execute on the ordinary keyboard, and thus does the Jankó keyboard make the piano, what it has often been called, a veritable 'house orchestra.' It is not nearly so difficult for the student to master the technic[sic] of the Jankó, as to become efficient on the present keyboard" (Dolge, 1911).

Nevertheless, the Jankó layout today lingers in even greater obscurity than the Dvorak layout. Dolge reasons: "Like all epoch-marking innovations, this great invention is treated with indifference and open opposition. … The piano virtuosos and teachers of the present day are opposing the Jankó keyboard because its universal adoption would mean for them to forget the old and learn the new. The music publishers object to it, because their stock on hand would depreciate in value, as the Jankó keyboard naturally requires different fingering than that now printed with the published compositions." A classic case of a path-dependent standard!

American pianist and engineer Paul Vandervoort has worked to revive the Jankó keyboard. In 1976, he spoke to *Keyboard* magazine about his adaptation of the layout: "No new keyboard stands any real chance of being widely adopted unless it offers performers all the good characteristics of the standard keyboard, plus some other features valuable enough to make converting from the old system to the new a worthwhile undertaking. Since my keyboard makes it possible for everybody to play faster, transpose more easily, and reach larger chords without breaking them, I'm convinced that it satisfies these conditions" (Vandervoort, 1976).

Once again the notion surfaces of features “valuable enough” to make the switch. The same argument is made by critics of Dvorak, who assert that any advantage it has over QWERTY does not outweigh the switching cost for most people.

A 1986 demonstration of Vandervoort’s Jankó piano has about 265,000 views on YouTube as of April 2020 (Vandervoort, 1986). Many comments on this video offer encouragement; user PickShark says: “I love this so much. I'm learning to play piano and this just seems a million times more intuitive ... .” Others are more skeptical. Wilfried Lingenberg, a classical pianist, writes “That scales are played with the same fingering in all tonalities is, for most purposes, not an advantage but a serious disadvantage. Classical composers were very skilled in using the asymmetric conventional layout in order to optimise playability according to anatomy.” This argument suggests that confirmation bias reinforces path dependence: people rationalize their choice of standard even in light of later reasons to switch.

The Jankó keyboard has compelling advantages over the original layout in a way that is different from Dvorak over QWERTY. Dvorak’s claimed advantages are quantitative improvements in typing speed and wrist strain, while Jankó allows previously impossible techniques as Vandervoort demonstrates in the video. Nevertheless, the end result in the market has been the same.

IPv6

We commonly think of IP addresses as looking like this:

`216.3.128.12`

The protocol that uses this format is called IPv4, and it has been in use since the Internet began. There are 32 bits of information in an IPv4 address, so the number of addresses is 2^{32}, about 4 billion. In 2019, internet-connected devices numbered about 26 billion (Bustamante, 2019). The reason to replace IPv4 addresses is then as straightforward as any: there are more internet-connected devices than possible IPv4 addresses. IPv6 solves this problem for the foreseeable eons by having an address that is four times as long. An IPv6 address looks like this:

`2001:0db8:85a3:0000:0000:8a2e:0370:7334`

Often, zeros are omitted to save space:

`2001:0db8:85a3:::8a2e:0370:7334`

Though this may seem only to delay the problem of address exhaustion until there are more devices, 2^{128} is in fact monstrously bigger than 2^{32} and the internet will have to double in size 96 times before IPv6 addresses are exhausted. But since the standard's development by the IETF in 1998 and its official Launch Day promoted by the Internet Society in 2012, only 25-30 percent of Google requests are over IPv6 as of 2020 (Google, 2020). Progress toward IPv6 adoption slowly (fig. 3), largely by necessity.

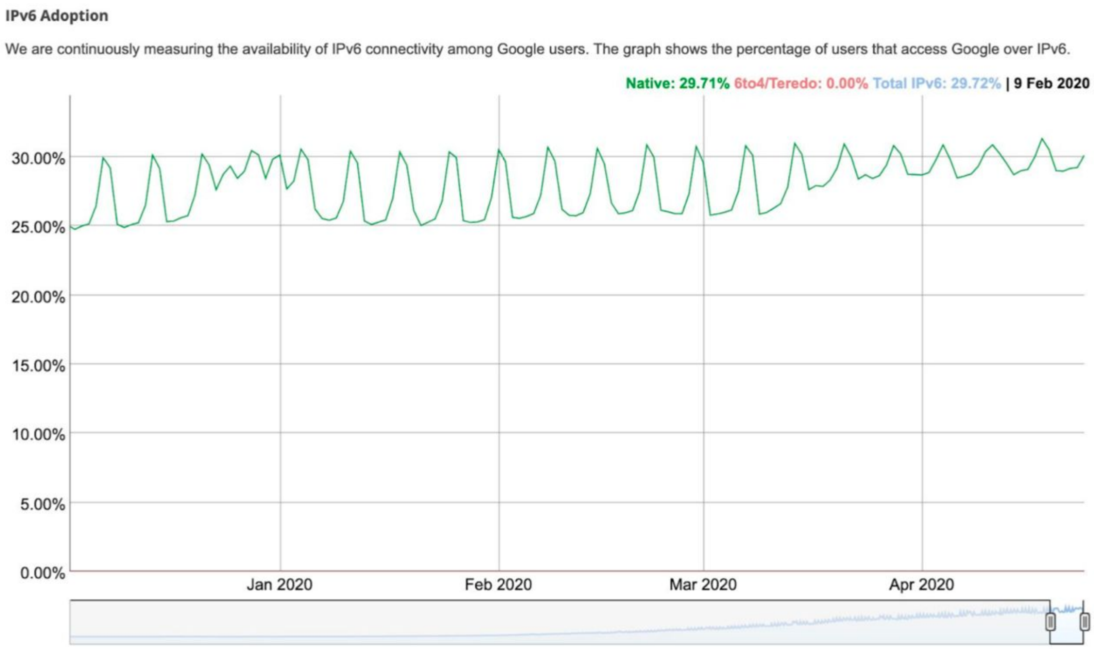

Figure 3. Percentage of Google packets sent over IPv6, Dec. 2019 to Apr. 2020 (Google, 2020).

In the 1980s, IPv4 was developed as an experiment by researchers for the Defense Department, but was so successful that, according to the co-inventor of IP Vint Cerf: “I honestly thought that if the Internet idea actually worked that we would then build a production version of it, and instead what happened is that [IPv4] got loose into use! We’ve been using the experimental internet design since … 1983 when we turned it on” (Cerf, 2014). The early engineers just wanted to get something working, with low anticipation that the project would be wildly successful. Now co-founder and Vice President of the Internet Society, Vint Cerf attests that “It’s been a long time since these standards were put in place, and it’s time to get with the program” with IPv6 connectivity (Cerf, 2018).

This illustrates the problem that even with a long-term plan for a technology, a communication barrier can lead to the proliferation of an inferior standard. In this case, the IP engineers did not communicate well enough to users that IPv4 was intended as an early prototype, resulting in IPv4’s widespread use and creating a Y2K-esque scenario which is still being resolved one network at a time.

Reluctance to switch to IPv6 has a visible impact on its adoption rate over time. Personal devices such as smartphones often support IPv6 natively, while many enterprise networks have been slower to adapt their existing infrastructure. As a result, the global adoption rate on weekends is about 30% compared to 25% on weekdays. Starting in mid-March this year, the effect of the COVID-19 quarantine has lessened this weekly trend since many more are staying home.

Refuting Liebowitz and Margolis

Paul David refers to skeptics’ arguments as using “Oompha-metrics.” He is referencing a response to his paper from D. McCloskey, who says the adoption of a new standard “is a matter of oomph.” David points out that this term is subjective: “despite the many occasions on which the term is invoked, ‘oomph’ itself still has yet to be clearly defined, much less subjected to measurement. (Although clearly the concept refers to some cardinal magnitude—since it is something that we don’t seem to have ‘enough’ of—even the appropriate unit of measurement remains unspecified. It is, perhaps, the ‘oompha’?)”

Resistance to a proposed alternative standard often boils down to such reasoning. The switching cost is too large compared to the benefit derived from switching. The new standard lacks “oomph.” But the switching cost is essentially a constant, while the benefit lasts as long as the new standard is used over the old. So the “oomph” needed to destabilize an existing standard depends entirely on the time scale over which the costs and benefits are considered. As the time scale increases, any switching cost incurred goes to zero compared to the benefit society receives from having switched. But this big picture is sometimes not the one considered.

Paul Vandervoort prefaces his response to Mr. Lingenberg: “Considering (1) your age, (2) the vast amount of time you have invested into mastering the conventional keyboard, and (3) your focus on classical music, I would not recommend that you learn to play a Janko.” Lingenberg is implicitly considering the choice of layout for his personal use over the rest of his life, not which should be the dominant layout in the market.

This is the reason Liebowitz and Margolis’ definition of third-degree path dependence is too restrictive. It assumes that the aggregate of individual interests approximates the interests of the society. While this is often true, the society lasts longer than any individual in it. If everyone in the society is considering only the costs and benefits of a standard over their own lifespan, then the society will not choose a standard whose longer-term benefits are foreseeable, despite every individual deciding rationally in their self-interest.

David attacks critics along these lines: “This suggests that the one thing that makes its worth having an ideé fixe -- such as the belief that path dependence cannot be important in economics—is the security of knowing that there is no fact or theorem that would ever be big enough (measured in oomphs or oompha’s) to dent or dislodge it from your mind.” By this he means that starting with the conclusion that costs due to path dependence are not “significant enough” relies on an arbitrary, subjective definition of “enough.”

Conclusions

In the natural world, path dependence in its strongest form is common. Complexity layers on top of complexity, leading to irreversible and inefficient outcomes like the giraffe's laryngeal nerve. By contrast, a rational actor can avoid bad decisions by analyzing options whenever it is advantageous and choosing the option with the greatest net benefit. But neither of these extremes describes the world we live in.

Society, unlike nature, has two important mechanisms which allow it to overcome such blunders - long-term thinking and global communication. Long-term thinking is what separates rational decisions from the outcomes of natural selection. It lets us step away from solutions that are only locally advantageous (such as making the nerve an inch longer) and toward solutions that will pay out in the long run (such as rerouting the nerve directly from the brain to the larynx). Global communication is what separates a single entity from a disorganized collective. Where long-term thinking prevents mistakes that become apparent over time, global communication prevents mistakes that become apparent over space.

Society is also *fundamentally* not a rational actor. It is a collection of people who can choose not to use the aforementioned tools at any time. When people choose not to exercise long-term thinking, they design band-aid solutions that cause problems later. When people choose not to communicate, incompatible competing standards are developed, or one dominates arbitrarily.

Humans emerged from the fallible process of evolution, and live in a chaotic, unguided universe. When there is similarity between society's decisions and those of a single rational being, it is through our own means and not by nature. The mechanisms which separate us from nature—long-term thinking and global communication—must be kept strong regardless of the free market's judgments on them, or we will find ourselves with a nerve wrapped around the aorta, powerless to move it where it should be.

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