EDITOR: Shane Greenstein, sgreenstein@hbs.edu

DEPARTMENT: MICRO ECONOMICS

Virtuous Cycles

Shane Greenstein, *Harvard Business School, Boston, MA, 02163, USA*

What shaped the economics of the microprocessor? In the beginning, replacement of components and redesign of equipment drove sales. Embedding logical instructions in the design of an integrated circuit changed calculators and scientific instruments. Those products found enthusiastic buyers in a generation of engineers and scientists raised on slide rules and vacuum tubes.

The rise of personal computers changed the focus. Apple and IBM won a format war, which benefitted their respective suppliers, Motorola, Intel, and IBM's semiconductor division. Third party software providers added applications. By 1985, IBM's PC division achieved sales that would have made it the third largest computer company, had it been free-standing. Not long thereafter, IBM lost control over the design to clones such as Compaq.

A new structure emerged. Original equipment manufacturers (OEMs) organized supply chains. OEMs assembled products that appealed to buyers. Microprocessor providers vicariously experienced the strategic triumphs and blunders of their OEMs and partners. Servers, smartphones, and other equipment arrived later, and adopted similar arrangements.

This structure has spawned a plethora of nomenclature, and that jargon is among the most misbegotten legacies of the microprocessor. With the intent to avoid jargon, and at the cost of oversimplifying historical details, today's column characterizes the big economic lesson that emerged from this structure. The economics are still with us today.

VIRTUOUS CYCLES

Collect all the economic forces behind innovation, and call them parts of a "virtuous cycle." The cycle is *virtuous* because operating one cycle *encourages* repetition rather than discouraging it.

0272-1732 © 2021 IEEE
Digital Object Identifier 10.1109/MM.2021.3116406
Date of current version 19 November 2021.

PCs can illustrate. Better and cheaper microprocessors raised the value of innovating in better software applications and peripherals. A better system induced 1) adoption and purchase by new users; and 2) faster replacement and upgrades by existing users. Growth in usage and sales, in turn, raised the value of innovations to achieve better and cheaper microprocessors, which raised incentives for better software again and again.

Any seasoned microelectronics participant recognizes this pattern. It is both a result of, and a contributor to Moore's law. That recognition is correct, but too narrow. Virtuous cycles can arise even without massive changes in the frontier of microprocessors. Complementary markets drive the cycles. Over the decades, credit also should go to the creation of, and improvements in retail outlets, fiber optics, digital switches, office printers, spreadsheets, browsers, and electronic mail, among many complementary spectacles.

ONCE EACH FIRM GAINED AN EDGE, THEN VIRTUOUS CYCLES HELPED REINFORCE COMPETITIVE ADVANTAGES, SOMETIMES AT THE EXPENSE OF BUSINESS PARTNERS.

Improvements did not happen on their own, to be sure. Over the years many firms sought to gain an edge. Bill Gates at Microsoft and Andy Grove at Intel created strategies to manipulate each part of the cycle for their firms' benefit. Books were written about those strategies. Because today's column aspires to avoid jargon, let us keep it simple. Suffice it to say, once each firm gained an edge, then virtuous cycles helped reinforce competitive advantages, sometimes at the expense of business partners. Both firms got rich executing this approach.

After this experience, nobody smart got surprised again. Confrontations between firms became heated. Whenever participants aspired to gain positions that they perceived would allow them to participate in virtuous cycles as leaders, they perceived the potential

to accumulate competitive advantages. When many firms could foresee the potential for a new and lucrative virtuous cycle, the jostling to gain an edge at the start became fierce.

As an example, around the new millennium the earliest versions of Wi-Fi catalyzed a virtuous cycle between wireless routers and wireless laptops. Let us make a long story short. Apple—led by the newly returned Steve Jobs—introduced the Apple Airport and wireless Mac. That motivated Michael Dell to start his own line of wireless equipment. External card makers briefly flourished. Intel sought to control further events, and invented Centrino, inducing and cajoling OEMs, including Dell, to fall in line. This was brutally fierce.

The growth of smartphones illustrates similar behavior and an additional point. Once again, many firms anticipated the smartphone and invested years in advance. Microsoft modified Windows. Nokia invested in Symbian. Apple proposed a touchscreen for a phone, music player, and software applications. Google bought Android, and gave discretion to hardware designers and software developers. Samsung and HTC had initiatives as well. I could keep going.

We all know what happened. This virtuous cycle was especially vicious for the losers. The iPhone and Android systems gained sales, and few users or app developers displayed appetites for a third system. That left no path forward for Nokia and Microsoft, and not for lack of trying. It may be hard to recall it, but that shocked contemporaries. Until then, these two firms had been, respectively, the most successful cellular handset maker and software firm ever.

VENDORS AND USERS

In competitive markets, virtuous cycles exhibit a nonintuitive feature. They allocate different levels of income and wealth to suppliers, but sometimes yield similar outcomes for users. When do virtuous cycles result in big or small differences to buyers? That is the key question.

Consider smartphones to illustrate. Don't you think the management at the number three firm has wondered what would have happened if they had stayed in the virtuous cycle instead of one of the other winners? For the sake of the argument, consider it. Remove, say, Android, and replace it with whomever you think deserved to be second among Nokia, Microsoft, or someone else. That replacement too would have been quite profitable after many years, and, Android would have gotten nothing. Summarizing the insight, winning early yields big differences in profitability.

On the other hand, consider users in any of these counterfactuals. Would the identity of the second winner have made much difference to users after the virtuous cycle operated? Every smartphone design gravitated toward the same basic goals in the long run. Any leader of smartphones would have benefited from relentless improvements and from microprocessors with capabilities well beyond those in the earliest PCs. Every design eventually sought to communicate by voice and text, store and play music, take photos and archive them, navigate an unfamiliar roadway, and allow a gamer to become self-absorbed in their phone while occupying a seat in a moving subway train. Any leader would have pushed the smartphone's usage to the same approximate place, resulting in a massive change in user allocation of leisure time. In other words, whether Android had been replaced with Nokia or Microsoft or Samsung or HTC or someone else, the user experience would have been similar in the long run.

MARKETS WORK BEST WHEN THE INCENTIVES AND REWARDS FROM INNOVATION ALIGN. YET, COMPETITION WITH VIRTUOUS CYCLES SEEM TO DELIVER LARGE FINANCIAL REWARDS IN RESPONSE TO TEMPORARY DIFFERENCES IN FIRM OFFERINGS AT EARLY MOMENTS, AND SOMETIMES THE REWARDS PERSIST OVER TIME.

Summarizing, smartphones illustrate one case. The user experience is similar with different suppliers. Yet, the experience of suppliers differs substantially and primarily based on early differences between them.

Do not misinterpret. Sometimes users would have had a much different experience with a different set of leaders. In some opportunities, such as smartphones, any sensible leader would have done the same sensible things, and outcomes for users are similar. In other settings, the user experiences diverge. That happens when leaders have persistently different capabilities, competence, organizational style, or visions.

This logic makes many economists uncomfortable. Markets work best when the incentives and rewards from innovation align. Yet, competition with virtuous cycles seem to deliver large financial rewards in response to temporary differences in firm offerings at early moments, and sometimes the rewards persist over

time. Luck appears to play a role at early moments. That is uncomfortable because rewards could become out of scale with the incremental differences between the talents, investments, and efforts of competing firms.

To be clear, it is not inevitable that rewards are aligned or out of scale. It is only possible and plausible, not inevitably.

IF THERE WILL BE A SERIOUS ECONOMIC DEBATE ABOUT THE PROFITABILITY OF GOOGLE, FACEBOOK, AND AMAZON, THEN THE ECONOMICS AROUND VIRTUOUS CYCLES PROVIDES THE UNDERLYING ECONOMIC FRAMING FOR THAT DEBATE.

More concretely, if there will be a serious economic debate about the profitability of Google, Facebook, and Amazon, then the economics around virtuous cycles provides the underlying economic framing for that debate. That is a subtle and difficult debate to conduct. Slogans on Twitter do not do it justice.

PRESENT ERA

The foregoing picked examples from the limelight, but virtuous cycles also show up in dimly lit places. For example, there has been a virtuous cycle in content delivery networks (CDNs) for years. Today Akamai finds itself in a leadership contest with Cloudflare, among others, while Google and Amazon and Netflix have developed their own CDNs. Most users have no idea how much this has improved large scale streaming, gaming, and data intensive electronic commerce. It is difficult to predict where this cycle will go next.

Machine learning has spent more time in the limelight, because the frontier programs have competed with—and beat!—the world's champions at Chess, Jeopardy, and Go. Other frontier AI simulates previously unmappable proteins and writes poetry, albeit, the text is still hilariously inartistic. Less visible but more important for the virtuous cycle, Nvidia led microprocessor designs that supported breakthroughs in algorithms. Google and then Facebook sponsored, respectively, Tensor Flow and PyTorch, and AWS has numerous efforts to match. That motivated a new round of microprocessor designs. Will these improvements generate additional gains in revenue and productivity, and fuel renewal of the virtuous cycle? Many firms have bet it will.

The questions about machine learning extends to medical instruments. The U.S. Food and Drug Administration (FDA) has approved a number of algorithms for use in hospital X-Rays and other equipment. Approvals for reimbursement from government insurance are imminent. If radiologists see the benefits and the revenue starts to flow to innovators, then this virtuous cycle could renew. To be clear, few observers care a wit about radiologists' revenue, nor which firm gains market share, but improvements in the accuracy and convenience of visual medicine could change the experience of many patients and surgeons. That could change the world. That is why I am rooting for the renewal of the virtuous cycle in this domain.

SHANE GREENSTEIN is the Martin Marshall Professor of business administration at Harvard Business School (HBS), Boston, MA, USA, and Co-Chair of the HBS Digital Initiative. He teaches in the Technology, Operations, and Management Unit. Encompassing a wide array of questions about microelectronics, computing, communication, and internet markets, his research extends from economic measurement and analysis to broader issues. His most recent book, *How the Internet Became Commercial* (Princeton, NJ, USA: Princeton Univ. Press, 2015), won the 2016 Schumpeter Prize for best book. Greenstein received a Ph.D. degree in economics from Stanford University, Stanford, CA, USA. Contact him at sgreenstein@hbs.edu.