Analyzing the Effects of COVID-era World Events on the GPU Market

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Winston Zhang

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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

Advisor

Kent Wayland, Department of Engineering and Society

Introduction

While virtually everyone likes to unwind in their free time by streaming movies and TV or playing video games, relatively few people think about the technology behind how moving images are displayed on their screens, the GPU. The graphics processing unit (GPU) is the component used to render computer graphics. When people think of the heart and brain of the computer, they think of the central processing unit (CPU), which is well equipped to perform complex calculations. However, the GPU's architecture allows it to take advantage of parallelism to perform vector and matrix calculations that are commonplace in graphics rendering. GPUs are commonly found in the following two form factors: they are either included with the CPU (known as integrated graphics), or they are housed in a separate, discrete/dedicated component, called a graphics card. Graphics cards generally have more capabilities in graphics rendering and have become so common that they are now colloquially referred to as "GPUs" despite containing electronics other than just the GPU chip. The graphics card has become a virtually ubiquitous piece of technology, as it is found in almost every device that has a screen or is meant to be plugged into one, due to the rise of personal computing, mobile devices, and at-home entertainment such as streaming and video gaming.

Almost all readers vividly remember the COVID pandemic and its consequences: lockdowns, social distancing, vaccine and mask mandates, financial crisis, but most importantly, the rampant inflation that caused the rapid and sweeping rise in prices of all consumer goods. GPUs and devices that use them were no exception, as the supply of GPUs decreased due to unprecedented supply shocks, resulting in almost nonexistent stock and egregiously high prices. Here, I hope to use STS theory to analyze the GPU shortage and identify the driving forces–both technical and social–that mutually shaped the GPU market during and immediately following the

COVID-19 pandemic. My discussion of the GPU market in a post-COVID world hopes to highlight trends of overreliance and technological inertia in the context of computing technology, as well as the supply chain and market as a means of allocating and distributing technology, and how interacting forces can threaten to dissociate such a system.

Background

In addition to graphics rendering, the GPU has other applications in computing, such as cloud computing, cryptocurrency mining, and artificial intellgence/machine learning. While many think of the GPU shortage as having purely been caused by the COVID pandemic, the aforementioned trends in computing, and by extension, the market demand for GPUs, were already on the rise before the pandemic. Thus, I must establish some background on how the GPU is used in these applications, "setting the stage", so to speak, before discussing how COVID changed the dynamic.

GPU Supply

Leading up to the COVID pandemic, the three main firms responsible for supplying GPUs to the US market were the following: Nvidia, Advanced Micro Devices (AMD), and Intel. Of these firms, Nvidia sells only discrete GPUs, and AMD sells both discrete GPUs as well as integrated GPUs. Before 2020, Intel only sold CPUs and thus only sold integrated GPUs until releasing their own discrete GPU model. According to a 2021 report by John Peddie Research, Intel had a majority of the GPU market with a 63% market share due to its dominance in the CPU market, with both Nvidia and AMD having less than 20% each. For the discrete GPU market, Nvidia held 73% of the market with AMD holding the remaining 27% (Dow, 2021). While Intel has its own manufacturing facilities, Nvidia and AMD both rely on Taiwan

Semiconductor Manufacturing Company Limited, or TSMC for short (Ridley, 2019). TSMC accounts for most semiconductor production in Taiwan, which had a 63% market share of the semiconductor industry (Lee, 2021).

Cloud Computing

Cloud computing is a model of IT infrastructure by which computing resources are consolidated under one large provider and rented out on a pay-as-you-go basis. For companies with variable IT infrastructure demand, such as an e-commerce site that experiences the most internet traffic during the holiday shopping season, the "pay-as-you-go" model presents itself as an economical choice. This is because "pay-as-you-go" elminiates need to pay for an extra in-house server to handle the increased seasonal traffic, which would then sit unused for the rest of the year, incurring energy and upkeep costs. Cloud computing is also an optimal infrastructural model for computing applications that involve a large amount of data/information, such as video streaming, as information can be processed and stored in a distributed system of several machines. To handle such a heavy workload, cloud systems require powerful GPUs.

Cryptocurrency

Cryptocurrency was created to be a decentralized medium of exchange, free from the influence of central banking and government regulation. It provided a level of anonymity, and users' currency could not be eroded in value by inflationary actions taken by central banks. Some cryptocurrency projects involve a computationally intense process called "mining", which results in more cryptocurrency being created and awarded to miners. Cryptocurrency mining requires a powerful GPU to efficiently mint enough tokens to offset the energy costs. While cryptocurrency has faced some government regulation in the recent past that has caused many to lose faith in it as a true medium of exchange, many still see it as a store of value, as well as an alternative asset

class to traditional assets such as stocks or bonds. Cryptocurrency adoption slowly progressed in the decade leading up to COVID, consistently reaching higher and higher price peaks every couple of years.

Artificial Intelligence/Machine Learning

While it did not have a direct effect on the GPU market during the pandemic, AI saw a boom in popularity directly following the pandemic with the release of OpenAI's critically acclaimed "ChatGPT," a large language model (LLM). AI models have been in development for years before ChatGPT and COVID, and involve an extensive training process on large datasets, which also requires powerful GPUs to process. The increase in popularity of AI and the reliance on GPUs has affected the GPU market in a manner that is yet to be fully observed. For example, Nvidia, a GPU manufacturer, is currently reaching all-time highs in its stock price (Howley, 2024). Market experts are unsure if the craze surrounding AI is a bubble, but Nvidia stock's upward price movement does not show any signs of slowing down and could have significant implications on GPUs as a technological artifact.

Theory

STS Theory

My STS research paper will use Actor-Network Theory (ANT), a commonly used theoretical framework in STS analysis. ANT frames systems as networks composed of participating actants, who are connected by dynamic and ever-changing relationships (Muniesa, 2015). Furthermore, ANT is useful for systems with many "moving parts", both figuratively and literally. For example, ANT can model the relationship between a computer and its user, with both the computer and the user being actants in a network, connected by a dynamically changing

relationship. ANT can then frame actants as nested networks with their constituent parts as actants, as the computer in our user-computer network can then be broken down into its keyboard, monitor, and tower, with each component capable of being further broken down. Since ANT places equal importance on the relationship between actants regardless of whether they are human or inanimate, or even conceptual, it can also be applied to sociotechnical systems, which involve the interfacing of people with technology, as well as human interaction using technology as an intermediate. Thus, ANT proves to be useful in its application to the GPU market, which is characterized by a supply and demand side, each comprised of various subgroups of people, some of whom have motivations for buying/selling GPUs, and some of whom whose motivations are partially unrelated to GPUs.

Economic Theory

In addition to ANT, an STS theoretical framework, I will also use various theories commonly used in economics to guide the discussion of market conditions. The primary economic theory that one must understand to analyze markets is the law of supply and demand, which is considered the basis of both micro and macroeconomics, just as Euclid's axioms are instrumental to mathematics. The law of supply and demand predicts how the interaction of supply and demand dictates how prices and volumes behave in a market (Perkis, 2021). Supply and demand are often modeled as mathematical functions, with quantity on the horizontal axis and price on the vertical axis. Generally, supply is an upward-sloping curve, as suppliers require consumers to pay a higher price for greater quantities consumed; conversely, demand is a downward-sloping curve, as consumers prefer to consume more goods at lower prices. Thus, the intersection of the supply and demand curves dictates the equilibrium price and quantity of the market, informally agreed upon by the free market and the supply/consumption preferences of its

actors. Changes in such preferences are reflected as shifts in the supply and demand curves and will result in the equilibrium conditions of the market changing as well.

Another important economic idea that stems from supply and demand theory is the concept of price-setting behavior. In a perfectly free and competitive market, suppliers and consumers are free with whom they do business, but certain economic conditions can create a market in which prices are set by market participants, rather than naturally settled upon. The most common instances of this phenomenon are when there is an asymmetry in supply and demand, whether it be a result of monopoly, oligopoly, or supply simply being dwarfed relative to demand. When consumers lack choice, the demand curve becomes a steep, nearly vertical line, representing the consumer's willingness to pay any price, allowing the supplier to engage in price-setting behavior to take advantage of the consumer's inelastic consumption preferences.

Analysis of the GPU market will frequently model the market as a single, isolated market, ignoring most exogenous but economically relevant variables. Readers who are more economically literate might take issue with this choice; it is true that the COVID pandemic brought about changes to consumption preferences, namely a general shift from spending on durable goods (electronics, automobiles, real estate) to nondurable goods (food, alcoholic beverages, and apparel) (Bureau of Labor Statistics, U.S. Department of Labor, 2022). Due to the unprecedented effects that quarantine and work-from-home policies had on the GPU market, both in changes in volume and price, I choose to ignore most exogenous variables for the sake of model simplicity.

Related Works

Due to how recent the COVID pandemic is, little scholarly literature exists on the subject of the COVID GPU shortage. The story has been extensively covered in the news and in economic journals, which the few existing scholarly articles do reference. The existing literature on the GPU shortage either focuses on the logistics and economics side of the story, or the technical side. One such source examines the effects of the COVID-era cryptocurrency market on GPU prices for gaming PCs but does not discuss the subject in-depth from the context of economics or STS (Lim & Wibowo, 2022). This topic has not been discussed at length in scholarly literature, as two of the most relevant and recent papers found that discuss the GPU shortage are senior theses, like mine, although both were not written by engineering students, but rather business and logistics, respectively (Khoury, 2021; Hajdu, 2021). Little of the existing literature attempts a big-picture approach to the topic, and most importantly, no papers exist on the topic that frame it in the context of STS theory.

Methods

A majority of evidence collected and sources consulted were secondary literature compiled from internet search results in the form of news articles and market research reports. Previous related scholarly literature also collected evidence in a similar manner. Oftentimes, sources that I collected before my literature review were discovered to have also been referenced in existing scholarly literature. Although the GPU shortage is a relatively well-known world event, sources were collected to provide documented evidence of events for the reader's reference. Sources were selected based on whether they were written by well-established, trusted authors, or whether they referenced primary sources. Sources were analyzed and annotated to

establish a chronological order of events, highlighting causes and effects, and making note of any possible quantitative econometric figures. These events were then organized based on whether they had supply-side or demand-side effects, which actors within the networks instigated it, whether the event affected other actors, and whether the effects were beneficial or adverse to the GPU market environment.

Results

After collecting and analyzing sources, a timeline of events was created, showing how world events affected the GPU supply and demand, how various market actors reacted to these changes, as well as the reactions of their counterparts. These events are summarized in this section.

Leadup to the Pandemic

Before the pandemic spread to the US, the stock market was already anticipating the effects of lockdowns and supply chain disruptions. Beginning February 20th, 2020, stock market investors began selling off shares. Eventually, the fall in prices led to a wide-sweeping, panic-induced selloff of securities, resulting in the stock market crash of March 2020 (Mazur et al., 2021). The stock market crash, like many previous crashes, was accompanied by a "flight to safety," an economic phenomenon in which investors sell off assets in favor of safer assets, such as bonds, as well as commodities such as gold and oil. Econometric studies show that such a flight to safety was observable in data for bonds, gold, and oil. (Papadamou et al., 2021; Löwen, 2021). As with other periods of economic downturn such as the Great Depression and the Great Recession, the stock market crash and flight to safety led to a severe decrease in aggregate demand, as corporate investment dried up, causing a general slowdown in the US economy.

More importantly, cryptocurrency was among the asset classes that investors flocked to, as evidenced by the increased volume of trading for Bitcoin following March 2020 (Sharma, 2021). Cryptocurrency, being viewed as a non-traditional asset class, saw the benefit of increased volume as it was in a perfect position due to its low prices following its 2019 correction. As the effects of pandemic supply shocks became more apparent, the US government injected an unprecedented amount of liquidity into the money supply to provide stimulus and bailouts (Schrotenboer, 2020). This act, in combination with rates being at a historical low, led many investors to be dissatisfied with central banking, and anticipating the value of the US dollar to be severely eroded, leading to even more volume in the cryptocurrency market, causing a steady growth in crypto prices (Nguyen et al., 2022).

While the events in markets for financial assets do not seem to be directly related to the GPU market, their effects set up cryptocurrency to become a major actor in the GPU market as the pandemic ensues and prices in the cryptocurrency market rise.

Onset of the Pandemic

In March 2020, the world quickly began to shut down in the face of COVID-19's rapid spread. In the US, local governments began closing schools, prohibiting large public gatherings, and shutting down businesses in an attempt to curb the spread (Katella, 2021). As companies, especially office-based businesses, were forced to close their doors, workers began to work remotely from home. In this transition, businesses and individuals started purchasing new desktop computers, laptops, and tablets to work from home. During this period, all major PC retailers such as Lenovo, HP, Apple, and more reported significant increases in sales in the second quarter of 2020 compared to Q2 2019 (Collins, 2020). To stay connected with their colleagues, workers began using cloud-based services like Zoom and Microsoft Teams to

communicate, with Zoom experiencing parabolic rates of growth, earning $330 million of revenue in pre-pandemic 2019, followed by $620 million in 2020 and $2.65 billion in 2021 (Richter, 2024). As the nation was forced to stay home, demand for other cloud-based services started to rise to accommodate the sudden lifestyle change, including online shopping, food delivery, and streaming. Amazon, Doordash, and Netflix reported increases in various growth metrics by more than 200 percent, all of which are flagship companies that have a majority market share in their respective sectors and run their online servers on Amazon Web Services cloud infrastructure (AWS) (Weise, 2021; Richter, 2022; Walsh, 2020). Cloud infrastructure providers began to aggressively expand their investment in cloud computing in response to the surge in demand, with Amazon expanding their investment in property and equipment related to AWS on an increasingly large scale, quarter after quarter (Morgan, 2022). In addition to increased consumer spending on amenities like shopping and streaming, the market also saw an astonishing 36% rise in spending on gaming, as Americans young and old alike looked for ways to stay entertained while waiting out the lockdowns (Baltrusaitis, 2020). The network surrounding the GPU market was beginning to experience strain, as workers and consumers were buying personal devices en masse, and cloud infrastructure providers were investing in building more machines and data centers to keep up with the demand for cloud-based web services, all of which require GPUs. Cloud computing and personal computing, as demand-side actors in the GPU market network, applied significant demand-side pressure during the onset of the pandemic. The onset of the pandemic also saw an accelerating upward pressure, as news of the rapidly growing cryptocurrency market following the investor flight to safety spread like wildfire on social media, prompting Americans to dabble in cryptocurrency, due to a combination of boredom and fear (Kyriazis et al., 2023).

As demand rose sharply, GPU manufacturers and suppliers, the supply-side actors of the GPU market network were affected by stay-at-home measures and border closures just as hard. Lockdowns in Asia that kept factories from opening, effectively brought manufacturing, including computer chips and GPUs to a halt (Cho, 2022; Kihara & Leussink, 2020). Any existing supply could not reach the US consumer market due to stringent controls on exports. The result of COVID lockdowns was the supply-side and demand-side actors of the network pushing the supply and demand curves in opposite directions, resulting in a sharp increase in the market standard price of GPUs. GPUs were virtually impossible to purchase during the pandemic, first limited by supply, with their prohibitively high costs remaining high for the proceeding years - the Nvidia RTX 3080, launched during the COVID pandemic, had a suggested retail price (MSRP) of $499 and went for $1200 at launch, and climbed to $2100 several months later, all with no alleviation in the strained supply (Hollister, 2021). The rise in GPU prices also affected gaming consoles, as well as used GPUs.

As the general demand for GPUs rose due to lockdowns and work-from-home measures, prices across the cryptocurrency market continued to rise, while the stock market remained volatile. Some saw an opportunity in the growing cryptocurrency market, opting to mine cryptocurrency using GPUs. While some cryptocurrency miners simply ran their personal computers, the GPU market saw a rise in purchases for new GPUs to mine cryptocurrency on dedicated mining machines, with some people taking it to an extreme by maintaining large “mining farms” of multiple computers. Cryptocurrency miners and traders, excited to extract gains from the rapidly growing cryptocurrency market, enroll in the GPU market network in large numbers, competing with gamers and other consumers for the limited supply of GPUs. As suppliers release what little supply they have in limited runs, scalpers hijack the network as

demand-side actors and try to take advantage of the euphoria-induced prices by using bots to purchase GPUs and gaming consoles, engaging in price-setting behavior by reselling them at a higher price (Dunn, 2021). In addition to scalping, other immoral market behaviors also emerged. Such behaviors include scammers posing as AMD attempting to convince people to "return" GPUs in a bogus recall, and scammers selling "used GPUs" to customers and shipping them an external housing for a current-generation GPU with the internals replaced by a much less capable GPU, or in some cases, simply an empty box with some paperweights inside (Liu, 2021; Hector, 2022).

In an attempt to alleviate the strained market conditions, manufacturers began to ramp up production to meet the demand as COVID restrictions eased up. One measure taken by Nvidia to alleviate the situation was to cut out the cryptocurrency market from the equation by introducing lite hash rate architectural changes to their GPUs, which are intended to throttle the GPU's performance if it detects that it's being used for mining cryptocurrency (Trevisan, 2021). The US government under both the Trump and Biden administrations, due to concerns over supply chain vulnerabilities and geopolitical concerns regarding Taiwan and China, intervened in the supply side of the market network, launching initiatives toward moving computer chip manufacturing to US soil, with TSMC agreeing to build a plant in Arizona (Kharpal, 2021; Swanson, 2020; Office of Public Affairs, U.S. Department of Commerce, 2024).

Late/Post-Pandemic

In the late pandemic, the steadily growing cryptocurrency market quickly developed into a bubble, which popped in the early months of 2021, triggering a year-long duration of losses across the market (Levy & Sigalos, 2022). In addition to a general market pullback from the dramatic price gains, developments in the financial sector, such as the SEC announcing new

regulations for cryptocurrency firms, as well as the Federal Reserve raising interest rates, the cryptocurrency market quickly experienced a loss and eventual reversal of momentum. In the following months, the broad selloffs of cryptocurrency brought many cryptocurrency firms close to insolvency, with FTX declaring bankruptcy. Additional regulatory developments, such as China banning digital currencies, as well as the IRS requiring cryptocurrency investment and transactions to be reported on tax return Form 1040, took away the flexibility and anonymity that made cryptocurrency such an appealing alternative to fiat currency (Ranganathan & Zhen, 2024; Taxpayer Advocate Service, Internal Revenue Service, 2021). The proverbial nail in the coffin came soon after when Ethereum, second in trading volume to Bitcoin, switched from the previously established proof-of-work consensus mechanism to the new proof-of-stake (Eberhardt, 2023). Proof-of-work was a competitive consensus algorithm, that verified transactions by requiring miners to solve cryptographic puzzles in exchange for newly minted Ethereum as a reward; proof-of-work, by nature of being tied to miners competing to solve puzzles, was what made cryptocurrency such as Bitcoin and Ethereum so reliant on GPUs. Proof-of-stake, on the other hand, ensured consensus via a random selection of verifiers, with a preference for those holding more Ethereum (The Investopedia Team, 2023). Proof-of-stake presented itself to be a consensus alternative that was more secure in the event of a network attack, and also more energy efficient, as the network no longer relied on millions of GPUs running at once to verify transactions. Unfortunately for miners, the switch from proof-of-work to proof-of-stake made it impossible to mine the second most popular cryptocurrency.

All of these blows to the cryptocurrency market hurt miners, many of whom chose to quit mining and recover some of their hardware investment by selling their GPUs on the secondary market. Suddenly, crypto miners went from being a demand-side actor in the network to

supply-side, flooding the market with used GPUs, before ultimately disenrolling from the network (Klotz, 2022). The cryptocurrency crash that converted GPU demand into supply, in addition to manufacturers' increased production, led to excess supply (Kunert, 2019). As manufacturers AMD and Nvidia were preparing for a new generation of GPUs, both engaged in price-setting behavior, substantially cutting prices to merchandisers to clear out inventory, resulting in current-generation GPUs going for dramatically discounted prices compared to their MSRP (Hollister & Warren, 2022).

GPU-adjacent developments following the shortage lead us to where the GPU market is today. The release of next-generation GPUs leaves consumers with a sour taste in the mouth, as Nvidia takes advantage of its increased market share following the pandemic to engage in price-setting behaviors once again. Consumers expressed discontent with the higher prices of 4000-series Nvidia GPUs, which deliver little improvement upon the 3000 series, to which Nvidia's CEO infamously rebuts that "Moore's law is dead", that expecting large leaps in GPU power is a thing of the past (Orland, 2022). The popularization of AI following the release of OpenAI's ChatGPT in late 2022 led to trillion-dollar investments in the tech sector to chase AI-related gains, ultimately raising revenue and stock price of GPU manufacturers, due to AI's reliance on GPUs to train models. AI is seen as enough of a disruptive technology that the US government banned the export of AI-capable GPUs to China soon after. Toward the beginning of 2024, the SEC approves a cryptocurrency ETF, making it a more legitimate and accessible asset class in the eyes of the financial establishment (Juang, 2024). Despite all these changes expected to raise GPU prices, price movements are not as dramatic relative to those during the pandemic, as the lack of significant supply-and-demand asymmetry creates a more stable market network.

Analysis

In the decade leading up to the COVID pandemic, an actor network surrounding the GPU assembled, with manufacturers and retailers as supply-side actors, and cloud computing, personal computing, and cryptocurrency as demand-side actors. In normal economic conditions, the network was stable, as there was no supply-demand asymmetry to strain network relationships. Most of the market network interactions were limited to supply-supply interactions in the form of competition between GPU manufacturers, as well as supply-demand interactions in the form of users purchasing GPUs. Furthermore, the lack of supply-demand asymmetry and network strain also meant that demand-side actors would rarely interact with each other, as each technology is disjoint apart from a GPU dependency and has little to do with any other demand-side actor, so much so that an ANT framing appears to make little sense. In the absence of demand-demand interactions, each demand-side technology could be framed in isolation using another STS framework, namely the mutual shaping of technology and society, as each technology discussed was developed as a solution to some problem or desire in society. Most interestingly, these technologies appear to be solutions that oppose each other in terms of their approach: cloud computing is a model of centralized IT infrastructure allocation that promotes flexibility, scalability, and cost reduction; conversely, cryptocurrency rose as a decentralized distributed system with the intent of taking power away from centralized banking and the financial establishment. The same dichotomy can be seen when comparing cloud computing to personal computing, as the rise of personal devices such as at-home computers, mobile phones, and gaming consoles originates with a desire to bring general-purpose computation into the home instead of the laboratory, and to similarly bring video entertainment out of movie theaters and arcades. Over several decades, computation and entertainment have become increasingly

accessible to the average consumer as CPUs could process workloads at greater speed and capacity, GPUs could render pictures with greater fidelity, and storage drives could hold more media with higher picture quality. As computing in the home grew in power and speed, cloud computing as a centralizing force began to rise in opposition to personal computing, with the advent of outsourced server-side computation as opposed to client-side, the most notable example being the rise in popularity of streaming services, which allowed users to access music and movies over the internet on demand, as opposed to having to download media first. This trend is exacerbated by recent attempts to bring gaming to the cloud, such as the now-defunct Google Stadia, Xbox Cloud Gaming, and Amazon Luna (Mangalindan, 2020).

The unfolding of events in the GPU market following the COVID pandemic induced a sudden strain on the actor network, which was brought about by unprecedented changes in supply-demand dynamics in the economy as a result of societal change, such as movement and interaction of people in their personal and working lives as a result of lockdowns and social distancing, as well as changes in liquidity preference and risk tolerance in the financial asset market. The pandemic-induced collapse of supply and explosion of demand that resulted in exorbitant GPU prices which put significant strain on the actor network caused the demand-side actors, normally disjoint and noninteractive, to suddenly have to compete over limited supply, transforming a stable network of equilibrium market conditions into an unstable, hypercompetitive market network, which gave rise to scalping, scamming, and overall feelings of resentment among GPU user groups. The high prices and low inventories of the COVID-era GPU market led to the actor network being in danger of dissociation. However, dissociation was not possible, as pandemic conditions would not allow the high demand for GPU technology to

subside, and no proper substitute existed for GPUs, highlighting a significant technological inertia surrounding the GPU.

Conclusion

We find that the GPU shortage, though a complicated network of various actors and motivations, can be boiled down to a system in which pandemic-induced restrictions caused a sudden and virtually complete elimination in supply, as well as a sudden spike in aggregate demand for GPUs across various user groups for various motivations. This sudden and significant asymmetry in supply and demand explains the astronomically high prices for GPUs that were seen in 2020 and 2021. We see that the various actors in our GPU-centered network are mostly disjoint and only related in their reliance on GPUs and that they come together to form an unstable network due to limited supply, which remains strained throughout the pandemic due to the ubiquity of GPUs and the reliance on GPUs in multiple technologies. The strained and unstable GPU market, as a result of supply-demand asymmetry and the GPU's status as a non-substitutable good, reveals a technological inertia surrounding the GPU that has existed for many years but reached a critical point that was aggravated by sociological factors.

Future works, whether sociotechnical or economic, could examine variables that my analysis chose to neglect for the sake of brevity. As previously mentioned, exogenous variables such as consumer spending behaviors were not accounted for, but are highly relevant to such an analysis. For example, the GPU shortage was a result of a larger shortage of computer chips, which similarly affected the automotive industry by generating upward pressure on overall prices. This effect is seen in an increase in the relative importance of private transportation (including cars and car parts, new and used) in the US Bureau of Labor Statistics's Consumer

Price Index (CPI), which tracks changes in American consumption preferences across various categories, as well as the inflation of prices within each category (Bureau of Labor Statistics, U.S. Department of Labor, 2022; Bureau of Labor Statistics, 2024). The ubiquity of computer chips in consumer products means there is a greater economic story with myriad exogenous macroeconomic factors to be analyzed, as opposed to the relatively small microeconomic model used in this study. An increase in relative importance for GPUs and GPU-dependent technologies & services across the entire CPI would serve as a piece in the puzzle concerning shifting consumption preferences, and how deep-seated the technological inertia surrounding GPUs is. Performing a more encompassing study on all consumer goods affected by the chip shortage could reveal trends in how hardware and software mutually evolve and shape each other, and how the crisis in manufacturing and supply brought upon by COVID may have affected the world of computing.

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