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THESIS

**THE U.S. FINANCIAL SYSTEM AS A NETWORK:
INSIGHTS AND IMPLICATIONS FOR
HYBRID WARFARE**

by

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June 2020

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IMPLICATIONS FOR HYBRID WARFARE**

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ABSTRACT

This thesis builds a network representation of the U.S. financial system using data that is processed automatically from the U.S. Federal Reserve. We develop computational tools to import and clean the overall quarterly holding amounts in the financial accounts of the United States Z.1 report for the current and historical quarters. We use this curated data to create a network representation of the financial system and then to analyze the network to identify the most important monies and players based on rankings, analysis of network structure, and visualizations of different dimensions of the network. By studying this network structure, we obtain insight into potential vulnerabilities and changes in the financial system over time.

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List of Acronyms and Abbreviations

ACH	automated clearing house
AUM	assets under management
BAE SAI	BAE Systems Applied Intelligence
BIS	Bank for International Settlements
CEO	Chief Executive Officer
CDO	collateralized debt obligation
CMO	collateralized mortgage obligation
CDS	credit default swap
CHIPS	Clearing House Interbank Payments System
CLO	collateralized loan obligation
CMO	collateralized mortgage obligation
DoD	Department of Defense
DHS	Department of Homeland Security
DoT	Department of the Treasury
DTCC	Depository Trust & Clearing Corporation
DDoS	distributed denial of service
EESA	Emergency Economic Stabilization Act
ETF	exchange-traded fund
EU	European Union

FFoF	Federal Reserve Bank Flow of Funds
FRBNY	Federal Reserve Bank of New York
FRB	Federal Reserve Board
FBIIC	Financial and Banking Information Infrastructure Committee
FSSCC CIPHS	Financial Services Sector Coordinating Council for Critical Infrastructure Protection and Homeland Security
FSSSP	Financial Services Sector-Specific Plan
FSB	Financial Stability Board
FSM	financial stability monitor
FSI	financial stress index
FSVM	financial system vulnerabilities monitor
FW	financial warfare
GDP	gross domestic product
GSE	government-sponsored enterprise
HW	hybrid warfare
IBF	international banking facility
IEB	Import-Export Bank
IoT	Internet of Things
IMF	International Monetary Fund
IRA	individual retirement account
JCPOA	Joint Comprehensive Plan of Action
MBS	mortgage-backed security

MPT	Modern Portfolio Theory
NDS	National Defense Strategy
NPS	Naval Postgraduate School
NSA	National Security Agency
NSS	National Security Strategy
NBFI	non-bank financial intermediary
NEC	not elsewhere classified
NYSE	New York Stock Exchange
OCC	Office of the Comptroller of the Currency
OFR	Office of Financial Research
OTC	over-the-counter
PDF	portable document format
PLA	People's Liberation Army of China
PNNL	Pacific Northwest National Laboratory
PCA	principal components analysis
SEC	Securities and Exchange Commission
SIFMA	Securities Industry and Financial Markets Association
SLA	savings and loan association
SSA	Social Security Administration
SSI	Strategic Studies Institute
SUNY	State University of New York
SWIFT	Society for Worldwide Interbank Financial Telecommunication

TIPS	Treasury Inflation-Protected Security
UAE	United Arab Emirates
UMD START	University of Maryland Study of Terrorism and Responses to Terrorism
UN	United Nations
USASOC	U.S. Army Special Operations Command
USAWC	U.S. Army War College
USG	United States government
USN	U.S. Navy
VaR	Value at Risk

Executive Summary

Warfare is continually evolving, and modern warfare incorporates hybrid elements that often target important infrastructure to achieve military goals. The financial system is a critical infrastructure sector; we rely upon it, whether explicitly or implicitly, for nearly every facet of our daily lives. It supports other critical infrastructure sectors and U.S. national security.

U.S. adversaries have recognized the importance of the financial system to U.S. power for decades and seek to leverage U.S. infrastructure vulnerabilities to overcome our advantages in traditional warfare. When adversaries specifically leverage vulnerabilities in the financial system, they engage in financial warfare. We define financial warfare as an attack that targets either money, which is any store of value that can be exchanged between two parties; players, who engage in financial transactions; or operators, who facilitate financial transactions.

Financial warfare attacks are occurring more frequently at a time when several trends, such as shifting demographics and increasing levels of U.S. debt, are likely either to continue encouraging those attacks or amplify the damage from them. Many organizations, including the Federal Reserve, Department of the Treasury, Office of Financial Research, and others, have devoted significant efforts to understanding vulnerabilities in the financial system. We employ a different approach for identifying vulnerabilities which builds upon previous work: creating a network of the financial system, which provides us with a different perspective on potential vulnerabilities.

We begin to create the network by first establishing a set of criteria for its underlying data. The data must be comprehensive, in that they cover the most significant monies, players, and operators; manageable, in that they balance granularity with the ability to aggregate the data; reliable, in that they come from a trusted organization; regular, in that they are published with enough frequency to allow for timely network creation and analysis; and confirmable, in that data from multiple sources largely agree. We identify several sources which meet most or all of these criteria, such as the Federal Reserve, Bank for International Settlements, and Securities Industry and Financial Markets Association. We focus the efforts of this thesis on the Federal Reserve Bank Flow of Funds (FFoF) to lay a foundation that will be built upon by future work.

We specifically focus on end-of-quarter sector holding amounts of each money tracked in the FFoF. We develop computational tools to import and clean the overall quarterly FFoF report and holding amounts for the current and historical quarters. Our curated data is a critical end-product; we use it to create a network representation of the financial system and then analyze the network to identify the most important monies and players based on rankings, analysis of network structure, and visualizations of different dimensions of the network, including temporal changes between network iterations.

Using a point-in-time approach, we observe the same monies and sectors appear in different elements of our analysis and visualizations. These monies and sectors are either highly connected in the network, represent a concentration of capital, or both. Highly connected monies and sectors are vulnerable due to the possibility that damage from an attack, such as instigating an intentional crisis of confidence, can affect a large number of other monies or sectors. Examples we observe include the Non-Financial Corporate Business and Non-Financial Non-Corporate Business sectors and the Corporate and Foreign Bonds money.

Monies and sectors with a high concentration of capital are vulnerable because of the potential for a high dollar reward (from an attacker's perspective) and because they may represent relatively few points of failure. Examples we observe include the Private Pension Funds and State and Local Government Employee Defined Benefit Retirement Funds sectors.

The sector Households and Non-Profit Organizations is an example of a sector that is both highly connected and has a large concentration of capital. Sectors such as this are systemically important.

We are able to identify different vulnerabilities by observing changes in the financial system over time, rather than relying on a single point-in-time. For example, we identify the Government-Sponsored Enterprises (GSEs) sector as a potential vulnerability due to its increased importance to the Home Mortgages money, and the Loans market generally, from Q4 2008 to Q3 2019. We note that GSEs did not appear in any of the point-in-time visualizations or analyses as an important node.

Our work is limited in several ways. Although the financial system is global in nature, our work considers only the U.S. financial system. Therefore, we are unable to determine the ramifications that the failure of a component of the global financial system would have on

the U.S. financial system. In addition, there are a number of activities for which it is not possible to obtain data, including financial transactions carried out via cryptocurrencies, via so-called “dark pools,” which are owned by financial institutions and which allow investors to engage in financial transactions privately; and via criminal activity. These and other enterprises likely account for significant financial transactions that cannot be captured by the techniques described in this thesis. Finally, the network we create focuses on monies and players; it does not include operators. Operators are critical to the stable functioning of the financial system. As such, they represent another possible avenue for financial warfare attacks.

Our reliance on the FFoF data creates other limitations. Although the FFoF contains data on many significant monies and players, there are several it does not, especially derivatives. As such, our network cannot capture the impact of those missing monies and players. Also, the FFoF is published only quarterly. In some instances, this is too infrequent to allow timely analysis. For example, during the 2008 financial crisis, the failure of key financial institutions and the crisis of confidence that precipitated a drop in the prices of certain monies unfolded over approximately two weeks. Furthermore, the tables in the FFoF do not have the granularity to determine which sectors are directly connected to one another and must use their connections via mutual monies as a proxy.

All of these limitations could be addressed in future work by incorporating additional FFoF data and/or additional data sources.

Our network analysis is oriented only from a defensive perspective of the U.S. financial system. Future work has the potential to gain different insights by taking an offensive approach towards the U.S. financial system.

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So long, and thanks for all the fish.

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CHAPTER 1:

Introduction

Modern warfare increasingly involves actions other than conventional attacks carried out with kinetic weapons between two or more state actors. The growth in terrorist activity by non-state actors over the last two decades has dominated discussions of national security, but the use of unconventional tactics and even attacks by state actors are recently on the rise. This blend of traditional and non-traditional attacks has become known as hybrid warfare.

1.1 Hybrid Warfare Defined

The term *hybrid warfare* is meant to reflect the changing nature of warfare, but it is often criticized as “lacking a clear definition” (Hartmann 2017) due to varying definitions given by different groups. Hartmann (2017) defines hybrid warfare as

a creative combination of civil and military ways and means that are deployed in a synchronized manner. The political aim of state or non-state actors that conduct hybrid warfare is to preserve or create non-democratic regimes and increase strategic options to enhance their power in international relations.

Lasconjarias and Larsen (2015a) define hybrid warfare slightly differently as

the true combination and blending of various means of conflict, both regular and unconventional, dominating the physical and psychological battlefield with information and media control, using every possible means to reduce one’s exposure. This may include the necessity of deploying hard military power, with the goal of breaking an opponent’s will and eliminating the population’s support for its legal authorities.

These are two of many definitions of hybrid warfare. For the purposes of this thesis, we use the definition given by Lasconjarias and Larsen while also acknowledging the importance

of Hartmann's emphasis on the ability of both state and non-state actors to wage hybrid warfare.

Russia's invasion of the Crimean Peninsula in 2014 is a prominent and ongoing case study of hybrid warfare (see, for example, the collected volume of essays in Lasconjarias and Larsen 2015b). Before and after the invasion, Russia utilized social media to spread disinformation and foment discontent with the Ukrainian government in the eastern part of the country. For example, Russia's efforts on Facebook were so pervasive that in 2015, then-Ukrainian President Petro Poroshenko called directly on Facebook Chief Executive Officer Mark Zuckerberg to assist Ukraine in fighting Russia's disinformation campaign (Priest et al. 2018). Russian-backed separatists had a more insidious use of Facebook to target (literally) the Ukrainian military. Separatists used Facebook to identify and contact the families of Ukrainian military personnel to tell them their sons or daughters had been killed. Many of those families then called their loved ones to confirm what they had been told. Separatists used the resulting increases in cell phone activity in certain areas to train their artillery fire (Brown 2018). In addition, Russia attacked Ukraine's electrical grid, thereby undermining Ukraine's ability to fight back (Cain 2019). Attacks on critical infrastructure — such as the transportation, water, financial, communication, or power systems, among others — are classic examples of hybrid warfare.

1.2 Hybrid Warfare and U.S. Critical Infrastructure

There is growing evidence of hybrid warfare being conducted at home within the U.S. For example, media outlets have increasingly reported over the last several years about malware implanted via cyberattacks in the systems of American power and water plants (Sanger and Perlroth 2019). These reports echo warnings from the Department of Homeland Security (DHS), which is responsible for the protection of most U.S. infrastructure, of threats to that infrastructure.

DHS now designates 16 sectors as critical infrastructure, which the agency defines as

sectors whose assets, systems, and networks, whether physical or virtual, are considered so vital to the United States that their incapacitation or destruction would have a debilitating effect on security, national economic security, national

public health or safety, or any combination thereof. (Department of Homeland Security 2019)

Most of these sectors, such as agriculture, water, and energy, have been heavily studied to protect them from attacks. One sector, however, has received relatively less scrutiny from a national security perspective, despite being the only one which underpins every other sector and which is the beating heart of U.S. power: the financial system.

1.3 The U.S. Financial System

The U.S. economy is currently the largest in the world in absolute terms from many perspectives. Nominal U.S. gross domestic product (GDP) stood at \$22.3 trillion as of October 2019, approximately 50% larger than China's, the world's second largest economy (International Monetary Fund 2019a). Financial system companies comprised more than 8% of U.S. GDP, ranking third of the 22 industries tracked by the Federal Reserve (Federal Reserve Economic Data 2019). In the second quarter of 2019, U.S. debt from all levels of government, businesses, and households and non-profits totaled more than \$77 trillion, more than three and a half times U.S. GDP (Windenberger 2019).

Still, the sizes of the U.S. economy and its financial system do not fully reflect their importance. It is far more important to recognize that no other sector can operate without money or the means to use it. Both are provided by the financial system, which is partly illustrated by the fact that 80% of all capital in the U.S. is raised in financial markets. In just the stock and bond portions of those markets, turnover (i.e., how often financial instruments like stocks and bonds are bought and sold) annualized to nearly \$307 trillion in 2019 as calculated from Securities Industry and Financial Markets Association (SIFMA) statistics (Securities Industry and Financial Markets Association Statistics 2019a,b; Swing Trade Systems Trading Days Calendar 2020), a value nearly 14 times larger than U.S. GDP. Furthermore, the U.S. dollar is the world's most widely used reserve currency. It comprised nearly 62% of all global foreign exchange reserves as of the second quarter of 2019, more than three times the share of the euro, the world's next leading reserve currency (International Monetary Fund Data 2019). The dollar's status as the world's premier reserve currency largely allows the U.S. to avoid exchange rate risk and reduces borrowing costs.

Changes to the financial system therefore affect every aspect of the U.S. economy in some way. For example, “chasing yield,” a prominent activity that led some investors to buy the type of mortgage monies that contributed to the 2008 financial crisis, manifested itself via different investors and other monies in 2008 and still in others today. The integral nature of the financial system, its dynamic behavior, and U.S. advantages in conventional warfare make the U.S. a prime target for the reemergence and evolution of a particular type of hybrid warfare: financial warfare.

1.4 Financial Warfare Defined

The importance of the financial system to U.S. power has not gone unnoticed by potential adversaries. In 1999, Colonels Qiao Liang and Wang Xiangsui of China’s People’s Liberation Army of China (PLA) published a book titled *Unrestricted Warfare*, in which they argued that non-military actions would be necessary to overcome advantages held by the U.S. military. Their observations pertinent to the financial system include the following:

Financial war is a form of non-military warfare which is just as terribly destructive as a bloody war. . . [though] no blood is actually shed. Financial warfare has now officially come to war’s center stage. (Liang and Xiangsui 1999)

The authors further assert that man-made stock market crashes, attacks on financial instruments, and cyber attacks on the financial system would be central features of modern warfare. To understand what constitutes financial warfare, we first define three broad categories which characterize all financial systems.

Money comprises the first category, which is much more broad than its typical colloquial usage suggests. Here, we define *money* to mean a store of value via any financial instrument or physical or digital asset which can be bought, sold, or otherwise exchanged between two or more parties. Common examples include physical or digital currencies (what is commonly thought of when referring to money), stocks (shares of ownership in a company), bonds (debt contracts of companies and governments which yield interest to the bond owner), or precious metals, such as gold. Unless otherwise noted, any later use of the word money in this thesis uses this definition.

Players comprise the second category of the financial system and are the active participants in a financial system who engage in a financial transaction. Such transactions can include buying, selling, and trading monies or entering into the contracts upon which those monies are predicated. Examples of players include individuals, who might take out a mortgage or buy and sell stocks for their retirement portfolios; multinational banks who lend the money for those mortgages or provide financial services for other firms; the U.S. Treasury and other municipalities, which finance government activities by selling bonds; the Federal Reserve, which engages in a number of market activities; various types of funds, which pool capital and invest on behalf of shareholders; insurance companies, which provide money in the form of risk management tools; and many others.

Operators comprise the third and final category of the financial system. In contrast to players, operators do not actively engage in financial transactions; instead, they facilitate their execution. Operators are, in effect, the “plumbing” of the financial system. Examples of operators include automated clearing houses (ACHs), which handle payment processing and securities and derivatives transactions; the Society for Worldwide Interbank Financial Telecommunication (SWIFT), which is the only firm in the world that provides a global network to financial institutions to communicate about their financial transactions; stock, bond, and derivatives exchanges such as the New York Stock Exchange (NYSE), which provide a platform for buying and selling those monies; depository, trust, and record-keeping activities such as the Depository Trust & Clearing Corporation (DTCC), which maintains secure transaction records; Fedwire, which assists in settling transactions; and new fintech payment platforms that increasingly provide non-traditional ways of transferring money.

With these concepts in hand, we now define *financial warfare* to be *any type of attack which targets money, players, and/or operators in the financial system*. Attacks can be physical, cyber, or financial and therefore can manifest in several ways. First, an attack on money could be intended to undermine its value, trust in the money itself, or both. Second, attacks on players or operators could interdict and/or hijack their operations. Interdiction prevents them from operating at all, while hijacking uses their operations in a manner in which they were not intended to be used. The damage from either interdiction or hijacking can also undermine the credibility of players or operators and by extension, trust in the entire financial system.

Financial attacks may be precise or widespread. However, even if an attack targets only a few monies, players, or operators, it is important to remember that the interconnected nature of the financial system can allow the effects of such attacks to ripple out to other parts of the financial system and the economy. As such, components and industries far removed from an attack's original targets may also suffer damage. Examples of damage indirectly affecting sectors include George Soros' attack on the pound sterling (Kuepper 2020), the Asian currency crisis that caused substantial losses in the U.S. (Carson and Clark 2013), and the United Arab Emirates (UAE)'s purported financial attack on Qatar (Zhdannikov 2018).

1.5 Protecting the U.S. Financial System

Both the National Security Strategy (NSS) and National Defense Strategy (NDS) acknowledge the importance of the economy to U.S. national security. However, this recognition is largely discussed in the context of unfair market competition (e.g., subsidies or forced technology transfers). The discussions in these documents entail *economic warfare*, which Shambaugh (2019) defines as

the use of, or the threat to use, economic means against a country in order to weaken its economy and thereby reduce its political and military power. Economic warfare also includes the use of economic means to compel an adversary to change its policies or behaviour or to undermine its ability to conduct normal relations with other countries. Some common means of economic warfare are trade embargoes, boycotts, sanctions, tariff discrimination, the freezing of capital assets, the suspension of aid, the prohibition of investment and other capital flows, and expropriation.

The end goal of both economic and financial warfare is the same, in that they aim to weaken an adversary's political and military power. There are some distinctions between both forms of warfare, such as in their focus and scope (e.g., financial warfare is generally precise and targets the financial system). However, the line between economic and financial warfare is increasingly blurred. For example, sanctions are often thought of as a form of economic warfare that targets broad sectors of an economy. However, the administrations of President

Trump and former President Obama implemented precise sanctions to isolate the targets from the global financial system (e.g., against Iran, associates of Russian President Vladimir Putin). The successes of these and similar activities demonstrate why detailed financial maps are a critical defensive or offensive component of hybrid warfare. Furthermore, such maps might assist in identifying illicit financial activity, which would support work done by organizations such as the U.S. Treasury.

The current U.S. Secretary of the Treasury, Steven Mnuchin, noted on 18 May 2017,

I'm probably spending 50% of my time on TFI [Terrorism and Financial Intelligence] issues. It is, I think, perhaps the most important issue, right now, as part of my job. (Mnuchin 2017)

As Secretary Mnuchin's comments imply, threats to the financial system are ongoing and require substantial resources to address those threats. The financial system is critical to the U.S. economy and U.S. national power, and it is important for organizations such as the Department of Defense (DoD) to devote additional resources to augment the efforts currently being made by organizations such as the U.S. Treasury, Federal Reserve, Homeland Security and Office of Financial Research (OFR).

The U.S. financial system's importance to American life and its attractiveness as a target for adversaries demand that it must be protected from harm. While protecting the financial system can take many different forms, any protective measure depends upon knowledge of the system's activities, weaknesses, and the implications of component failures. Moreover, the rapidly changing nature of the financial system (e.g., the introduction of new payment systems, crypto-currencies, and blockchain, which provides security but also prevents tracking bad actors) means protective measures may also have to change. Therefore, protecting the financial system ultimately requires a thorough understanding of the system's structure and a means of rapidly updating the view of that structure.

The financial system can be represented as a network with the right framing, and a network representation can be useful in several ways. First, a visualization of the network often reveals key structural characteristics. For example, a visualization of the financial system as a network can show sectors reliant upon a small number of components (i.e., money, players,

or operators) and possible indirect effects of component failures. Once vulnerabilities are identified, appropriate protective measures can be proposed, such as expanding the number of components or otherwise filling their roles should they fail in some way.

Second, the financial system is transient by nature, and therefore, any network of the financial system will necessarily change over time. Tracking changes in network structure as new data become available allows one to identify, for example, the introduction or exit of components or abnormal activity in the market. If new players or money were to emerge and grow quickly, whether in terms of capital, trading volume, or both, this could signal a new point of vulnerability in the markets which could place many sectors at risk.

1.6 Goals of this Thesis

This thesis builds a network representation of the U.S. financial system using data that is processed automatically from the U.S. Federal Reserve. We analyze the network to identify the most important monies and players based on rankings, analysis of network structure, and visualizations of different dimensions of the network. By studying this network structure, we obtain insight into potential vulnerabilities and changes in the financial system over time.

There are four primary goals of this work.

First, it should raise awareness of the network approach to modeling the financial system. As previously noted, a map encompassing as great a view of the financial system as possible that can also be produced quickly represents a protective approach that differs in key ways from current publicly available research. Furthermore, if this thesis is capable of creating a network of the U.S. financial system from publicly available data from which vulnerabilities can be ascertained, it is a reasonable and cautious assumption that U.S. adversaries possess this same capability. Therefore, it is imperative that senior decision makers are aware of the potential benefits (from a defensive perspective) and hazards (from an adversary's offensive perspective) of a network model of the financial system. Such a network would also assist in overcoming some of the information challenges associated with certain forms of analysis, such as wargaming.

Second, the visualization of the network must be sufficiently intuitive that it allows for qualitative conclusions to be drawn quickly. These initial insights can then be investigated

further via network analysis, which can also reveal vulnerabilities that are not immediately apparent from the network's visualization.

Third, building the network and its visualization must be able to be completed quickly enough so that new iterations of the network can be generated in near real-time as new data become available. This allows a user to analyze notable changes quickly, such as anomalous trading behavior or potentially dangerous build-ups of money in different sectors.

Finally, this thesis should lay the groundwork for creating networks of other countries' financial systems. For this work, we adopt a defensive approach to the U.S. financial system. Provided data are available, the approach utilized herein should be sufficiently adaptable to create networks of other countries' financial systems as well, for either offensive or defensive purposes.

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CHAPTER 2: Background

We begin by describing recent examples of financial warfare. We then briefly discuss some key structural elements of the financial system to contextualize how players and operators interact to aid in understanding how we might identify vulnerabilities. Next, we review some prior attempts at mapping the financial system and the shortcomings we later address with our approach. We end by describing how a network map might be used and the tools we employ for qualitatively and quantitatively analyzing it.

2.1 Examples of Financial Warfare

Imagine a person walking up to an ATM to withdraw cash or going online to pay bills, only to find they cannot access their accounts or that they were not receiving their paycheck. This is not merely hypothetical — customers of some of the country’s biggest banks, including Bank of America, BB&T, and Wells Fargo, were affected by outages in 2017, 2018, and 2019, respectively, lasting from a few hours to a few days (Herrera 2017; Rexrode 2018; Kunthara and Russell 2019). In one especially egregious example, TSB Bank in the UK was hit by an outage that lasted more than a month for some customers (Rumney 2018). In February 2020, Fidelity customers woke up to find that their account balances had gone to \$0; some of those customers were unable to access their accounts at all (Malito 2020).

Each of these outages were technical glitches, but malicious attacks have been occurring for years and could cause much greater damage. Russia decreased its holdings of U.S. Treasuries by 84% in a three month period in early 2018, in part due to U.S. sanctions on some Russian individuals and businesses (Egan 2018). In early 2019, China reportedly considered reducing its holdings of U.S. Treasuries as a result of the ongoing tariff disputes with the U.S. (Gibson 2019). Similarly, Former Secretary of the Treasury Henry Paulson stated in a 2014 interview that, in 2008, Russia encouraged China to dump its holdings of mortgage-backed securities issued by Fannie Mae and Freddie Mac on the global market, an attack on a money and players which could have inflicted significant damage on the mortgage market at a time it was already suffering (Peston 2014). A similar vulnerability may be building up again, as U.S. home prices exceeded pre-financial crisis levels in late 2016 (Orton 2016) and

have continued climbing since, which increases the leveraged positions of new homeowners in the mortgage market.

In 2010, hackers (who were suspected to be Russian) penetrated the NASDAQ exchange and stole much of its source code, with the speculated aim of helping to establish Moscow as a financial hub. The subsequent investigation into the attack found the hack could have instead disrupted the NASDAQ's operations, constituting interdiction of a player and operator (Riley 2014). In 2016, hackers hijacked the SWIFT account of the central bank of Bangladesh and used the network to place nearly \$1 billion in false orders, of which more than \$81 million were executed and never recovered (Schwartz 2016). This is one of several recent and successful hacks of SWIFT's network, which are hijacking attacks that also undermined trust in SWIFT's operations.

In recent years, hackers and gangs have stolen money directly from users (e.g., those of Sberbank, Russia's largest bank; see Townsend 2016) or from multiple banks directly (e.g., the Carbanak cybergang, which stole up to \$1 billion from as many as 100 different institutions; see SecureList 2015). These examples illustrate the importance of identifying nodes (e.g., players and operators) who have high possible reward per attack; large nodes who present relative ease of attack; or nodes which offer the opportunity for repeated attacks; monies that lack traceability; and more. Network mapping is designed to promote the identification of such vulnerabilities.

2.2 Financial Warfare Is Longstanding and Ongoing

Financial warfare provides opportunities for many types of actions by an attacker: direct or indirect, misattributable or unattributable. Examples begin just after the post-war period and have become more prevalent in recent years. Here, we discuss examples of attacks on money, players, and operators in turn.

Attacks on Money

An early prominent example of financial warfare in the post-war period occurred during the Suez Crisis. In 1956, the U.S. and U.K. withdrew promises to finance construction of the Aswan Dam. In July the same year, Egyptian President Gamal Nasser responded by nationalizing the Suez Canal Company, which had previously been owned and operated by

the British and the French. In October, the British and the French planned and executed an invasion of Egypt with the Israelis to retake the Suez Canal. American leadership under President Eisenhower opposed military intervention in Egypt, in part due to American opposition to similar intervention by the Soviets in Hungary occurring at the same time.

President Eisenhower was upset with the British for not keeping him apprised of their intentions. He first attempted to use diplomacy to get the British to back down. He did not want to respond militarily against an ally when they refused, so he used several financial strikes instead. First, he prevented the International Monetary Fund (IMF) and the Import-Export Bank (IEB) from extending credit to the U.K., whose economy was still recovering after World War II and dependent upon financing for much of its imports. Second, he threatened to dump all U.S. bond holdings of the pound sterling on the world market. Without external financing and with its currency under threat of devaluation, the British were forced to withdraw from Egypt less than a week after their troops had entered the country (Department of State Office of the Historian 2019; McMaken 2015).

Although President Eisenhower did not follow through with financial strikes against the U.K., the Suez Crisis illustrates two examples of attacks threatened against financial instruments. The first was withholding credit to the U.K. Given the state of the British economy at the time, this was an indirect strike against the pound sterling. The British were still recovering from World War II and relied on deficit spending to purchase critical goods from abroad, such as food and fuel. A lack of credit would have undermined the British economy and in turn devalued the currency, making these goods more expensive for the British and severely limiting their ability to import them.

Dumping pound sterling bonds on the world market would have constituted a direct strike against that money. On its own, dumping would require the U.K. to pay a higher coupon, or interest rate, to entice investors into buying newly issued debt instead of the increased supply of existing bonds in the world market. The impact of dumping would have been more pronounced due to the restriction of credit from the IMF and the IEB. Given that restricting credit could devalue the pound sterling, any pound-denominated bonds would carry greater currency risk because the pound would be likely to lose value relative to other currencies. The restriction of credit, currency risk associated with the pound sterling, and increased supply of pound sterling bonds could have frozen the British out of global credit

markets and prevented their ability to trade internationally.

Attacks on Players

The NASDAQ is an American stock exchange based in New York City, one of several owned by the financial services company of the same name. At the end of 2018, it was the world's second-largest stock exchange as measured by the market capitalization of the companies it lists, which is approximately 20% of total global market capitalization (Shukla 2019). In 2018, the value of the trading volume on the NASDAQ was greater than that of the next five largest stock exchanges combined (Statista 2018).

In October 2010, malware was discovered in the NASDAQ's servers. The hackers who planted the malware did so by leveraging so-called "zero-day exploits", which are vulnerabilities that either have not been discovered or have not been patched by the software's creator. It was initially believed the malware was capable of disrupting the NASDAQ's operations, and the investigation into the attack involved the National Security Agency (NSA), CIA, FBI, DoD, DHS, and Department of the Treasury (DoT). The investigation ultimately concluded that the attack was most likely perpetrated by Russian hackers attempting to steal the exchange's source code, possibly with the intent of establishing an exchange in Moscow. Although it also determined the malware was not capable of as much disruption as initially believed, the networks of several other major financial institutions were found to be vulnerable to the same zero-day exploits that enabled the hackers to penetrate the NASDAQ's servers (Riley 2014).

In June 2010, the United Nations (UN) passed sanctions against Iran in an effort to curtail its nuclear program, which were followed by additional sanctions from the U.S. and European Union (EU). The U.S. sanctions indirectly targeted the Iranian government by directly targeting two broad categories: firms involved in Iran's oil sector and foreign banks conducting business with Iranian banks (Sen 2018).

At that time, oil comprised nearly one-fifth of Iranian GDP (TheGlobalEconomy.com 2019). When U.S. sanctions went into effect, many insurers ceased underwriting policies for Iranian shippers. The sanctions against foreign banks had two effects. First, Iran was unable to access much of its assets stored abroad. Second, many banks would not process transactions for Iranian oil. Since most ports will not allow entry to cargo ships if they

are uninsured and many banks would not facilitate the sale of Iranian oil, its ability to sell oil internationally was severely curtailed (Erdrink and Lynch 2010; Saul and Cohn 2019). Before sanctions were lifted in 2015 as part of the Joint Comprehensive Plan of Action (JCPOA), more commonly known as the Iran nuclear deal, Iran's oil exports fell by more than half (Katzman 2019).

The U.S. targeted Iran again recently. In September 2019, the U.S. imposed sanctions against Iran's central bank. The sanctions effectively cut off Iran (a player) from the world's financial markets (Talley and Ballhaus 2019).

Attacks on Operators

SWIFT, an organization located in Belgium run by many of the world's largest central banks, provides a secure communications network to more than 11,000 financial institutions worldwide. Institutions primarily use the network to transfer money by placing orders with other institutions, which use the network to validate those orders (Zetter 2016).

In February 2016, a group of hackers gained access to the network of the central bank of Bangladesh to gain access to its SWIFT account. The hackers used the account to place fraudulent orders with the Federal Reserve Bank of New York (FRBNY), requesting a transfer of the bank of Bangladesh's funds to various banks throughout Asia. The fraudulent orders totaled nearly \$1 billion. Of those orders, \$101 million were executed; one bank was able to reverse a \$20 million transfer, but the remaining \$81 million was stolen and never recovered. The hackers' efforts to conceal their actions were largely successful and might have stolen significantly more money. However, a typographical error alerted an employee at the FRBNY and caused the employee to scrutinize the orders more closely. Other orders were not executed immediately only because the name of a bank to which funds were to be routed contained part of the name of an unrelated company which had been blacklisted for violating sanctions on Iran (Zetter 2016).

This attack is not isolated. Since 2015, at least six other attacks have hijacked the SWIFT accounts of different financial institutions. The attacks attempted to steal or have successfully stolen approximately \$42 million (Carnegie Endowment for International Peace 2017). Although SWIFT's network was not directly compromised, the attacks have been extremely financially costly to the institutions which use it. Furthermore, the attacks raise questions

about whether there are sufficient safeguards in place to prevent the execution of fraudulent orders, which undermines trust in SWIFT itself.

2.3 Today's Financial Vulnerabilities

The preceding examples illustrate that the financial system is vulnerable in a multitude of ways. The goals of an attacker can be financial (e.g., stealing monies, making a profit on manipulated markets, illicit movement of monies, avoiding taxes) or systemic (e.g., disabling critical financial system plumbing or infrastructure, creating a crisis of confidence in one or more players or monies, or destroying confidence in a player, money, or even a nation state). Making sense of financial warfare today requires understanding three important points.

First, financial warfare attacks are occurring more frequently in the *cyber domain*, due to increasing use of the cloud and the Internet of Things (IoT), digitization, and changes in consumer and business behavior to embrace these changes. Hackers successfully used Trojan malware to steal hundreds of millions of euros from German bank customers by disguising bank withdrawals via the display of unchanged online bank balances (Harris 2009). Further, small groups of actors are able to have an outsized effect, such as the London Whale, who lost \$6.2 billion for JPMorgan Chase (Hurtado 2016), or Navinder Sarao, who caused the 2010 Flash Crash of major U.S. stock markets that initially eliminated more than \$1 trillion in equity value (Kenton 2019b). It is important to note bad actors who do not have the resources to mount traditional warfare attacks are able to execute financial warfare attacks. As such, these actors' ability to influence the financial system is one of many reasons a full view of it is necessary to determine its vulnerabilities.

Second, while digitization has increased the frequency with which the financial system is attacked, cyber warfare is not the only way by which to conduct financial warfare. The 2010 sanctions against Iran provide one such example; Russia's urging of China to dump U.S. mortgage-backed bonds is another (Peston 2014). Therefore, it is important not to take a parochial view of financial warfare by considering it only as a subcategory of cyber warfare.

Finally, financial warfare attacks on either money, players, or operators often impact one of the other categories. During the Suez crisis and with sanctions on Iran, players were indirectly targeted (the U.K. or Iran) by directly targeting money (bonds and credit or

insurance and banking access). The hacks of banks' SWIFT accounts directly damaged players (the banks themselves) and indirectly impacted an operator (SWIFT, by undermining trust in its operations). The indirect effects of direct attacks help to demonstrate the connections between money, players, and operators and thus why a network is ideally suited to represent the financial system.

Moreover, the interconnectivity and overall complexity of the financial system means that it does not require an intelligent adversary for there to be widespread disruption, as noted by the 2008 global financial crisis. Analyses of the causes of the crisis point to exposure to subprime mortgages, which in the U.S. grew from an estimated 15% of all mortgage originations in 2001 to 48% of all originations by 2006 (Baily et al. 2008). Debt monies whose values were predicated on pools of mortgages (one form of a derivative) also grew significantly in size and value during this time. Several large financial institutions, including Lehman Brothers, used this form of money as collateral to obtain short-term loans for their day-to-day operations. Two of the largest players (JPMorgan Chase and the Bank of New York Mellon) who accepted this money as collateral severely curtailed their lending based on this collateral to highly leveraged players. As some of these players lost access to critical sources of funding, they either failed or required bailouts. The subsequent system-wide credit freeze affected sectors which still operated using day-to-day financing predicated on other forms of collateral but which had no exposure to the mortgage market.

The bottom line is that you cannot build financial system resilience if you cannot “see” its vulnerabilities. Analyzing the system in a manner that captures the complexities of the preceding example requires a specific view of the financial system. Fortunately, substantial and important work has been done by many organizations to attempt to generate such a view of the financial system,

2.4 Prior Mapping Attempts

There have been a number of previous attempts to represent the structure of the financial system using maps.

2.4.1 Heat Maps

Several organizations have generated some form of map of the financial system, including heat maps. Heat maps have some conceptual similarities to a network approach, in that they generally can be produced quickly (if constructed appropriately) and visualize data to highlight areas of potential concern. Prior mapping efforts provide important insights. However, the approach we employ differs in key ways, which we describe.

The IMF produces a heat map (pictured in Figure 2.1) they publish for public review, which is meant to give some insight into global financial stressors. The IMF's heat map is global in scope; while it does include the U.S., its focus is not U.S.-specific (as might be expected of a worldwide institution) (McLaughlin et al. 2018). The IMF's heat map flags areas of potential vulnerability by focusing on major economic areas. Our approach differs from the IMF's heat map in that we focus specifically on the U.S. and create a network to identify vulnerabilities (in terms of monies, players, or operators) instead of economic areas.

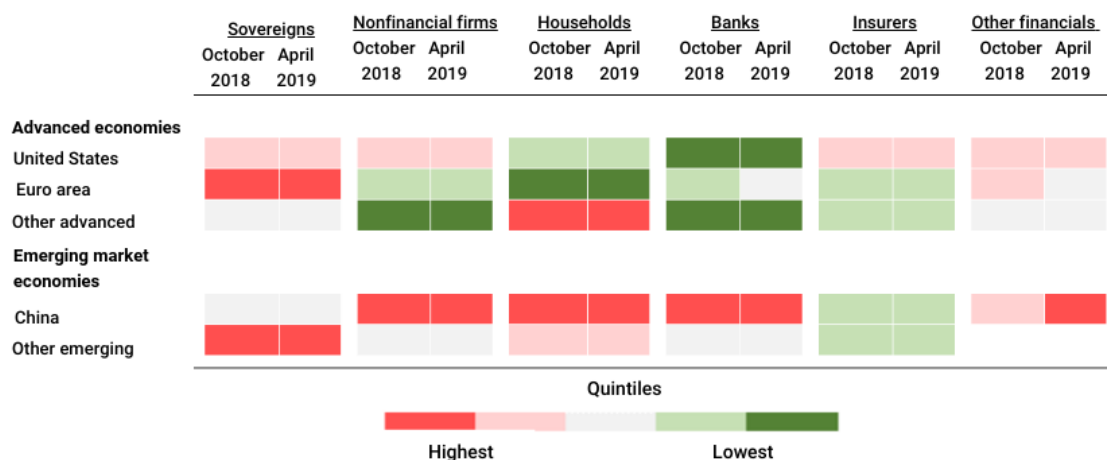
The Federal Reserve also generates a heat map, which focuses on the U.S. financial system. Their heat map is not released to the public (McLaughlin et al. 2018). However, Aikman et al. (2015) discuss how the heat map is constructed. The Federal Reserve uses 44 different indicators to build their map; the indicators are similar to those used by the OFR's financial stress index (FSI) and are chosen after reviewing existing literature (Aikman et al. 2015). As noted previously, the FSI's U.S.-specific indicators do not overlap with the money, players, or operators used in this thesis, which is largely true of those used by the Federal Reserve as well.

In addition to the FSI, the OFR currently publishes the financial system vulnerabilities monitor (FSVM), which replaced the financial stability monitor (FSM) (Office of Financial Research 2019) in 2017. The FSVM is also a heat map (pictured in Figure 2.2); it is predicated on 58 indicators. As with the IMF and Federal Reserve's heat maps, the indicators differ from the network approach we employ, in that they flag potential vulnerabilities by economic areas by estimating risk.

The manner in which indicators are selected to build the Federal Reserve's and OFR's heat maps implies another important distinction with a network approach. As Aikman et al. (2015) note,

Weak spots

Vulnerabilities are elevated by historical standards. They tend to amplify the impact of adverse shocks and may increase risks to financial stability.



Sources: Bank for International Settlements; Bank of Japan; Bloomberg Finance L.P.; China Insurance Regulatory Commission; European Central Bank; Haver Analytics; IMF, Financial Soundness Indicators database; S&P Global Market Intelligence; S&P Leveraged Commentary and Data; WIND Information Co.; and IMF staff calculations.

Note: For households, the debt service ratio in emerging market economies is based on all private nonfinancial firms. Other systemically important advanced economies comprise Australia, Canada, Denmark, Hong Kong SAR, Japan, Korea, Norway, Singapore, Sweden, Switzerland, and the United Kingdom. Other systemically important emerging market economies comprise Brazil, India, Mexico, Poland, Russia, and Turkey.

INTERNATIONAL MONETARY FUND

Figure 2.1. IMF's heat map. The map focuses on major economic areas and flags areas of potential vulnerability. Source: International Monetary Fund (2019b).

Indicator selection began with a broad review of studies of financial stability vulnerabilities, including empirical studies and monitoring frameworks used by others in the official sector.

With those heat maps, the first step is to select indicators from a review of prior work, followed by building the heat map. In our approach, we use raw data first to build the network and then analyze it for potential vulnerabilities (from which indicators may be selected).



Figure 2.2. OFR's FSVM heat map. As with the IMF's heat map, the FSVM flags potential vulnerabilities by economic areas. Note the FSVM is U.S.-specific. Source: Office of Financial Research (2020).

2.4.2 Network Maps

Two organizations have generated networks akin to the one we seek in this thesis.

In early 2019, the Financial Stability Board (FSB) published the *Global Monitoring Report on Non-Bank Financial Intermediation*. Chen (2019) characterizes a non-bank financial intermediary (NBFI)'s activities in the following way:

A non-bank financial intermediary does not accept deposits from the general public. The intermediary may provide factoring, leasing, insurance plans or other financial services. Many intermediaries take part in securities exchanges and utilize long-term plans for managing and growing their funds.

While the FSB's report focuses on a limited number of institutions amongst those in the financial system, its illustration of interconnectedness helps to illustrate the network concept we use, as shown in Figure 2.3 below.

The FSB's diagram includes several characteristics we capture in our network. First, players (as aggregate sectors) form the nodes (the squares in Figure 2.3), which are sized according

to the player's asset total relative to the sum of all assets for all players. Second, players are linked via money (the arrows in Figure 2.3); the arrow's direction indicates “flow,” or investment from a lender in a borrower, from a lender (at the arrow's tail) to a borrower (at the arrow's head). While the thickness of an arrow is conceptually similar to the size of a node, it differs from a node's sizing in that an arrow's thickness is determined by the absolute size of the exposure, not the size relative to the sum of all exposures (Financial Stability Board 2019). Both a node's size and an arrow's thickness give immediate visual indications of a player and money's importance, respectively.

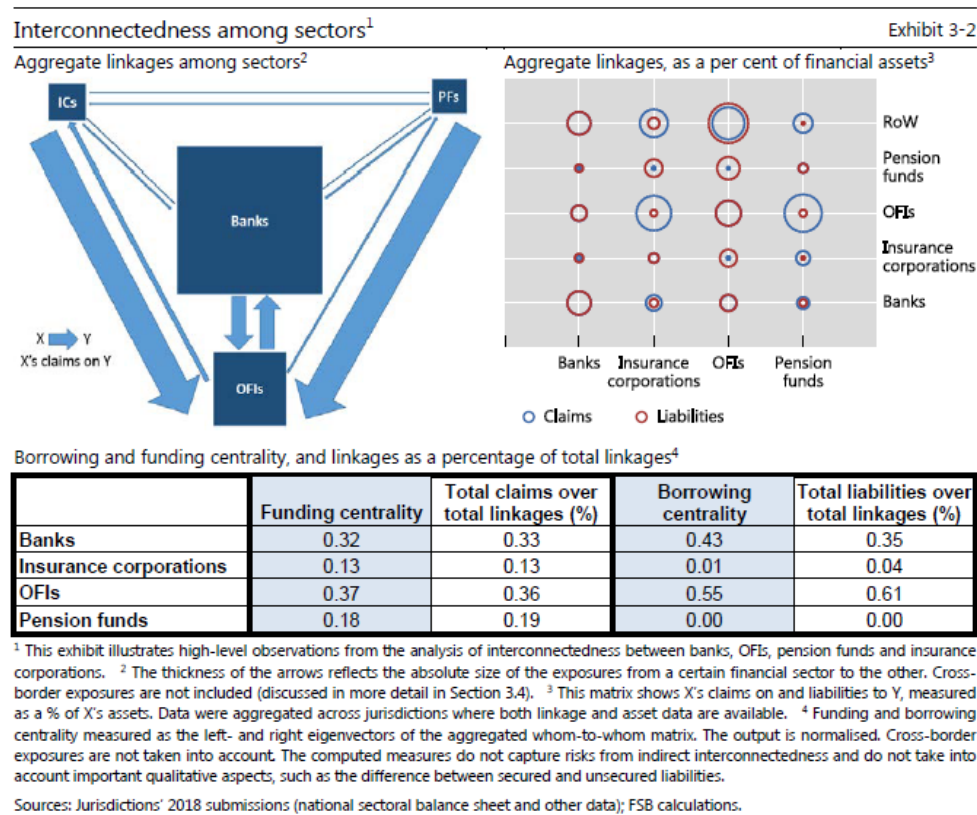


Figure 2.3. FSB's network representation. Squares are primary nodes representing players. The nodes are connected directly with arcs directed from asset- to liability-holders. The arcs are sized according to the size of the claims one node has on another. Nodes are sized according to their overall holdings. Source: Financial Stability Board (2019).

We add to the FSB's approach in two ways: we expand the network by adding more players

(nodes) and adding more monies (arcs). In doing so, we gain further insight into connections between players (with the inclusion of more monies as arcs) and a larger view of the financial system (with the inclusion of both more monies and more players).

The other institution to develop a map of the financial system is SBCC Group. SBCC created their map in 2014, predating the one created by the FSB. SBCC's map is reproduced in Figure 2.4, with permission from Tanya Beder, Chairman and Chief Executive Officer (CEO) of SBCC Group.

SBCC's map captures the same node characteristics as the FSB's map. In comparing Figure 2.3 and Figure 2.4, however, nodes are presented differently in the SBCC map; the two columns comprising each node (player) represent that player's assets (on the left) and liabilities (on the right). The constituent blocks of a column represent a form of money and are sized relative to the sum of that column (i.e., that player's assets or liabilities). SBCC's map also adds to the FSB map by incorporating more monies and players.

We build upon SBCC's map in several ways. First, the Federal Reserve currently releases files that accompany the Portable Document Format (PDF) release of the Federal Reserve Bank Flow of Funds (FFoF) which contain data which date back to 1945. When SBCC first created their map, those accompanying files did not exist. SBCC used automation where possible (e.g., PDF scrapers), but the lack of accompanying files limited this automation and required significant manual work, which slowed the creation of their map. The automation we implement combines historical and current data from the FFoF to create a large network quickly. Second, we leverage one aspect of the FSB's map, namely that arcs are sized according to the size of the claim, to build upon the SBCC map. Finally, by creating a network quickly, we create new visualizations as data become available to identify potential new vulnerabilities as they arise.

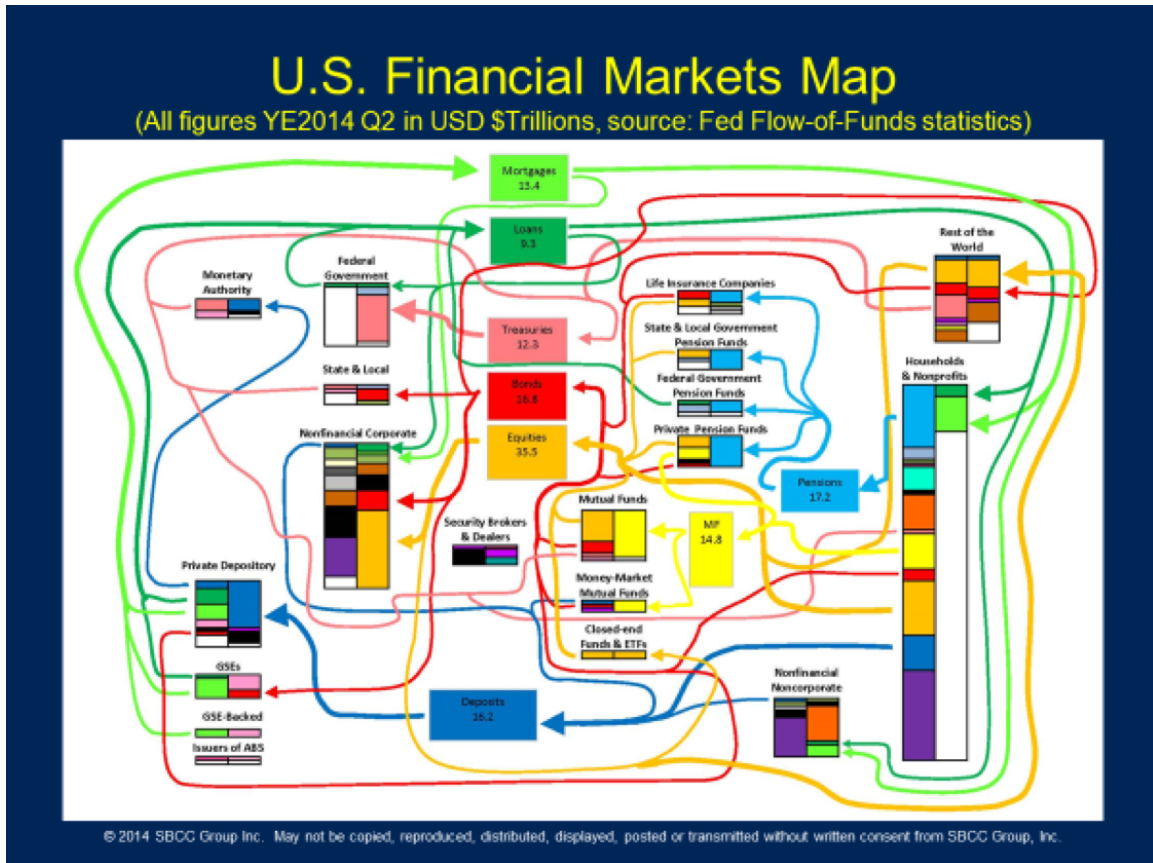


Figure 2.4. SBCC's network representation. Players are primary nodes which are represented with side-by-side columns. The left and right columns are that player's assets and liabilities, respectively. Each block within a column corresponds to a money. The block is sized according to the amount of that holding relative to the sum of all holdings. Arcs are directed from like-colored blocks from the asset columns of all players which own that money to an intermediate node representing the money corresponding to that block. Arcs are then directed from that intermediate node to the like-colored blocks in the liability columns of the players which owe that money. Source: SBCC Group (2014).

2.5 Using Maps for Vulnerability Analysis

There are several ways a map can be used to identify existing vulnerabilities or to identify potential new vulnerabilities as they arise within the financial system.

With a map, we can identify major participants (either players or operators) in the financial system. A major player is one which belongs to the group of players which collectively hold at least 80% of the assets or liabilities of a given market. Similarly, a major operator is one which belongs to the group of operators which facilitates at least 80% of money transfers within a given market. Under this definition, we can identify participants which are one of a few (or possibly single) points of failure. Major participants are more likely to be targets given their systemic importance.

We can also use a map to identify major monies. Major monies necessarily include large amounts of capital and often include a large number of participants. As such, an attack on a major money can either have a significant impact on a small number of participants or a relatively lesser impact on a large number of participants.

We can use a map to identify single points of failure. A market with relatively few participants is necessarily *concentrated*; if one participant were to fail in such a market, the risk is greater that the remaining participants would not be able to fill the gap created by that participant's failure. For example, this occurred during the 2008 financial crisis. At the time, JPMorgan Chase and the Bank of New York Mellon were the primary players providing short-term financing backed by certain forms of collateral. An attack on either player would have also been damaging to any players dependent on those short-term financing markets.

We can use a map to identify places of widespread impact. If a participant is connected to many other participants, damage from an attack on that participant has greater potential to spread to other participants. We can quickly identify highly connected participants by counting the arcs emanating from or directed to the participants in a map. In counting the arcs, we also consider the flows those arcs represent, which is the actual amount of a given money invested or borrowed by a participant. This context is necessary because a participant may be highly connected while many or all of its connections represent relatively small amounts. An attack on such a participant would be less likely to cause damage that spreads to other participants.

We can identify new participants and monies that represent new potential vulnerabilities as they arise between map iterations, as well as those which become less relevant or disappear from the financial system entirely over time. For example, many players either went bankrupt or were severely damaged during the 2008 financial crisis because of their exposures to subprime mortgages, the market for which had grown significantly in the years preceding the crisis. After the crisis, the number of subprime mortgage originations dropped substantially.

We can use a map to gain different perspectives into different markets, especially with respect to time. For example, mortgages can represent a connection between a lender and a borrower that lasts for up to 30 years, while equities trading represents a connection between the buyer and seller that lasts only a few days.

2.6 Contributions in Context

We now describe the contributions of the chapters to follow.

In Chapter 3, we present our overall workflow, with a focus on data curation. First, we discuss the process by which we select a baseline data source. Second, we detail the challenges we face in curating the data from our selected source and how we process the data into a dataframe. Finally, we describe the characteristics of that dataframe, which we use in to create our network.

In Chapter 4, we use our curated data to create a network representation of the U.S. financial system. We analyze the connectivity structure of the network to identify key structural features. We then comment on the implications of these features in terms of potential vulnerabilities.

In Chapter 5, we describe how to use our data curation and modeling technique to identify and understand changes in the financial system over time.

We conclude in Chapter 6 by discussing the results and insights gained from our models and analysis. We then discuss the assumptions and limitations on our work. We finish by proposing ideas for building upon our work in the future.

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networks with greater frequency (e.g., monthly or weekly), obtain different perspectives (e.g., trading volumes), or expand the network further (e.g., adding derivatives).

- ***Comprehensive***: The dataset must be broad and deep. It must cover the most significant players, operators, and monies while providing some granularity on the players' activities (e.g., their trading volumes or outstanding assets and liabilities).
- ***Manageable***: The dataset must balance the level of granularity and the ability to aggregate data. That is, we desire as much granularity as possible, provided we can aggregate the data in a way which allows us to focus on smaller parts of the network as necessary to avoid creating an unwieldy network which inhibits identification of market trends.
- ***Reliable***: The data comprising the final dataset must be reliable (e.g., from a trusted organization, such as the Federal Reserve). Any analysis is only as good as its underlying data, so the data source must be trustworthy.
- ***Regular***: The data must be published relatively frequently. Infrequently published data do not permit analysis of market trends as they occur.
- ***Confirmable***: Ideally, data are reconcilable between sources. Sources which confirm each other's data are more trustworthy than those which are not confirmable. It is important to note that given this is real-world data, there are sometimes discrepancies due to differences from the institutions reporting to the source in question. For example, the FFoF includes line items specifically noting such discrepancies. That said, the data sources must not be so far apart as to undermine the data's validity.

There are several sources of initial interest because they meet several of the criteria outlined above, including the Federal Reserve's FFoF, the Bank for International Settlements (BIS)' Statistics Warehouse, and SIFMA's Research & Data. Each of these sources are valuable because they cover a variety of players and monies to varying degrees of granularity. They also provide differing perspectives, such as players' overall holding levels of monies at a given point in time or transaction volumes in a given period of time.

We also recognize there are some shortcomings with these sources (e.g., the FFoF does not incorporate any detailed derivatives data and SIFMA often does not provide granularity for all the monies in our analysis). Furthermore, each source generally maintains its own format, which we must be address when aggregating data. For example, the FFoF and SIFMA data

cover many of the same players and monies, such as trading volumes or holdings. SIFMA provides more granular timeframes than the FFoF but does not always break out which sectors own which forms of money as the FFoF does. As another example, sources like the BIS cover some forms of money (especially derivatives) in much greater detail than does the FFoF.

For the purposes of this thesis, we employ the FFoF data, the categories of which are presented in Figure 3.2. These data cover a significant number of players and monies, provide enough granularity to gain analytical insight, and are published regularly and with some frequency (each quarter). Therefore, the FFoF data serve as a foundation on which we build a network which can later be expanded. We discuss the SIFMA and BIS sources to note they also contain robust, publicly available data which are useful for future work.

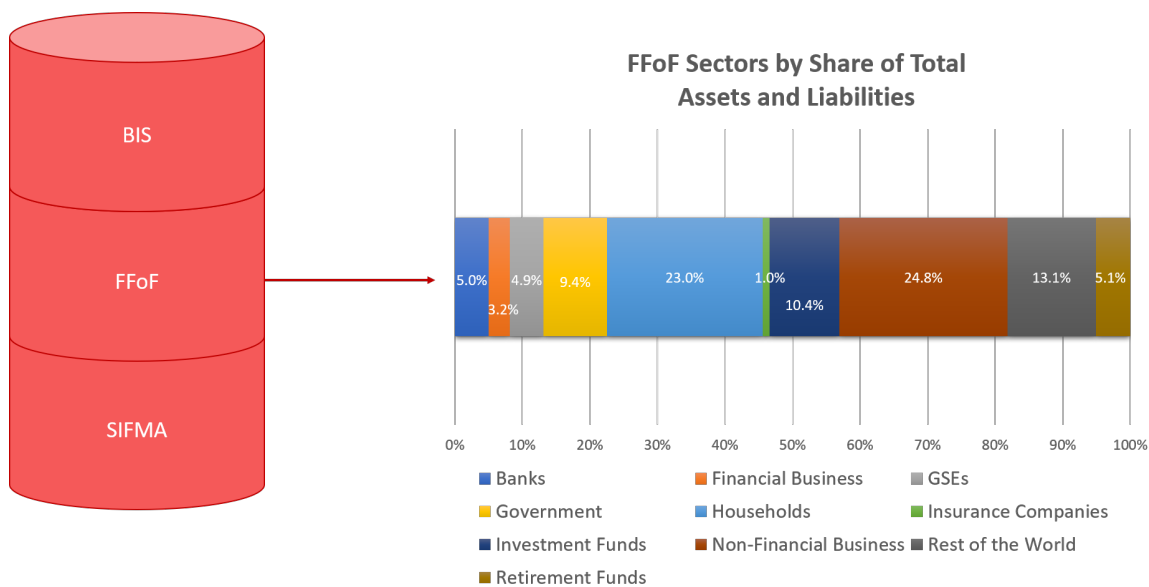


Figure 3.2. Financial categories found in the FFoF. The sectors in the FFoF have been grouped into similar categories. The categories are depicted by the total size of their outstanding asset and liability holdings to depict a basic understanding of the largest financial categories found in the FFoF data. Source: Board of Governors of the Federal Reserve System (2019).

3.2 Data Curation: FFoF Data

We provide a high-level perspective of the characteristics of the raw FFoF data and the process by which its various formats are programmatically cleaned and combined.

3.2.1 Raw Data Characteristics

The FFoF is released quarterly as a PDF file, with the underlying data available in comma-separated value (.csv) and plain text (.txt) file formats.

PDF Files: Tabular Data

The FFoF PDF lists data primarily in tables presenting different perspectives on financial information, such as overall transaction amounts, levels (i.e., total amounts of assets and liabilities) held at the date of publication, and balance sheets. In most instances, the information is presented in two different ways: a table shows a form of money, with amounts broken down by constituent sectors, or it shows a sector, with amounts broken down by constituent monies. For this thesis, we use the level view where tables represent monies with amounts broken down by constituent sectors.

Each PDF document also provides categorization of sectors and monies; that is, some sectors and monies are broken down further into sub-sectors and sub-monies. For example, loans are a parent money, with mortgages as one of its sub-monies; mortgages are, in turn, broken into more specific sub-monies, such as residential mortgages. In total, there are 35 money tables (L.200 to L.234) and 44 parent sectors and sub-sectors present across those tables. Figure 3.3 shows table L.204 from the FFoF PDF.

Data within a table are assigned a unique identifier. The identifier is an 11-character alphanumeric string, such as FL713120005 as shown in line 2 of table L.204 in Figure 3.3. The identifier indicates the type of information (e.g., the data are seasonally adjusted and that they represent levels); the money it represents; the sector holding that money; the money's classification (i.e., as an asset or liability for the sector); and whether the amount connected to the identifier resulted from a calculation done by the Federal Reserve. It is important to note that some identifiers are present in multiple tables, as the table for a parent money sometimes lists the identifiers presented in the tables representing its sub-monies.

L.204 Checkable Deposits and Currency

Billions of dollars; amounts outstanding end of period, not seasonally adjusted

			2017	2018	2018				2019			
					Q1	Q2	Q3	Q4	Q1	Q2	Q3	
1	FL793120005	Total liabilities	4229.8	4544.0	4360.0	4350.7	4382.2	4544.0	4443.5	4435.2	4617.8	1
2	FL713120005	Monetary authority	1819.7	2078.0	1884.9	1963.8	2043.0	2078.0	2027.5	1975.3	2111.8	2
3	FL713123005	Federal government cash and deposits	229.1	402.4	290.0	333.0	384.9	402.4	334.3	263.9	382.7	3
4	FL713124005	Due to government-sponsored enterprises	44.4	33.2	21.1	28.9	35.3	33.2	34.1	34.6	31.8	4
5	FL713122605	Deposits due to foreign	5.3	5.3	5.3	5.3	5.3	5.3	5.3	5.3	5.2	5
6	FL713125005	Currency outside banks	1540.8	1637.2	1568.5	1596.5	1617.4	1637.2	1653.7	1671.6	1692.1	6
7	FL763127005	U.S.-chartered depository institutions	2015.4	2053.7	2071.9	1982.1	1928.9	2053.7	1992.3	2027.2	2072.4	7
8	FL763123005	Federal government deposits	1.9	1.8	2.2	2.2	1.8	1.8	1.6	1.6	2.0	8
9	FL763122605	Deposits due to foreign	59.4	71.4	69.7	76.5	77.9	71.4	70.2	83.5	80.9	9
10	FL763129205	Private domestic deposits	1954.1	1980.5	1999.9	1903.4	1849.3	1980.5	1920.6	1942.0	1989.5	10
11	FL753127005	Foreign banking offices in U.S.	185.0	177.6	179.3	179.9	189.7	177.6	190.6	197.6	194.2	11
12	FL753122603	Deposits due to foreign	75.2	74.4	75.8	71.6	72.7	74.4	72.2	69.9	72.0	12

Figure 3.3. Sample of table L.204 from the FFoF PDF. Note the table, identifiers, classification, quarter, and amount match against the information in our Pandas dataframe found in Figure 3.5. Amounts are rounded to the nearest tenth in the PDF. Source: Board of Governors of the Federal Reserve System (2019).

CSV Files: Unique Identifiers

Each table has a corresponding .csv file. The file contains all the unique identifiers presented in the FFoF PDF, with amounts assigned to those identifiers going back to 1945 on a quarterly basis. The identifiers in the PDF differ slightly from those in the .csv and .txt files. In the .csv and .txt files, the identifiers include a suffix denoting whether the data are reported quarterly or annually. We use quarterly data in this thesis.

Text Files: Data Dictionaries

Each table has a corresponding .txt file that serves as the data dictionary for that table. Each line of the .txt file lists the unique identifier, the sector, the money, the classification, the line on which the identifier is found in the FFoF PDF, the table in which the identifier is found, the units (generally in millions of dollars), and notes on seasonal adjustments.

3.2.2 Data Challenges

We address several challenges posed by the FFoF data and note others which must be taken under consideration for future work.

Market Changes

The financial system changes frequently; as a result, the Federal Reserve frequently updates the FFoF data to reflect those changes as well. The updates manifest in two ways. First, the Federal Reserve adds new identifiers and drops old ones as sectors and monies are created or disappear. Second, some identifiers have zero values associated with them. This is a reflection of the first change — that is, a market which previously existed has effectively disappeared at the point in time when the Federal Reserve published that iteration of the FFoF.

Formatting Changes

The Federal Reserve has released the FFoF since the second quarter of 1996. They significantly updated the formatting of the FFoF PDF in the first quarter of 2013; the formatting has otherwise been consistent, but future analysts utilizing the FFoF data must review them when they are released each quarter to ensure no formatting changes have occurred which would necessitate updating the programming used to clean the data.

Also of note is that the .csv and .txt files were not included with the FFoF release until the first quarter of 2016. This is an important consideration because the Federal Reserve revises some of its data as more accurate information is gathered from reporting institutions. It is possible to capture such revisions beginning in 1996 by comparing sequential releases of the FFoF. However, the process of doing so would be highly manual without corresponding .csv and .txt files for those releases.

Categorization

Some identifiers are present in more than one table as a result of the categorization scheme described above. The categorizations for sectors and monies are laid out in the ‘List of Data Tables’ in the PDF. The categorization scheme is used across tables (e.g., L.209 to L.213 are sub-tables of L.208) and within each table (i.e., sectors are broken into sub-sectors). Therefore, we leverage the categorizations in the ‘List of Data Tables’ to include only the lowest category tiers to avoid including an identifier more than once in our final dataset, as we would otherwise overcount.

Different Data Files

Since different elements needed for processing the data are in the PDF, .csv, and .txt files, we leverage elements common to each file format to link the information in each of them. The only element common to all three is the unique identifier, which we use to retrieve data from the files and combine them into a single format.

3.2.3 Data Processing Tools

We use a variety of tools to import, clean, and combine the FFoF data.

Python

The Python programming language provides the overall architecture for the processing implemented for this thesis. We choose Python because of its flexibility and maturity, which are a result of the substantial number of libraries available for custom purposes (Python Software Foundation 2020b). Regarding the pre-processing discussed here, Python has native functionality which allows for reading .txt files line-by-line, which we use to read the FFoF's data dictionaries.

PyPDF2

PyPDF2 is a Python library which allows for 'scraping' a PDF to pull information from the file (Python Software Foundation 2020a). We use PyPDF2 to determine the categorization scheme from the level tables programmatically.

Pandas

Pandas is a Python library intended specifically for data analysis. The library's dataframe format for storing data allows for manipulations and calculations to be performed quickly that may otherwise require a slow, computationally intensive implementation (McKinney 2010). Pandas has functionality for importing .csv files into a dataframe, which is used to import the FFoF amounts. We combine the information found in the data dictionaries and the categorization scheme with the amounts in the .csv files to form a single Pandas dataframe.

3.2.4 Workflow

We briefly summarize the pre-processing workflow we implement with these tools. We present a visualization of our workflow in Figure 3.4.

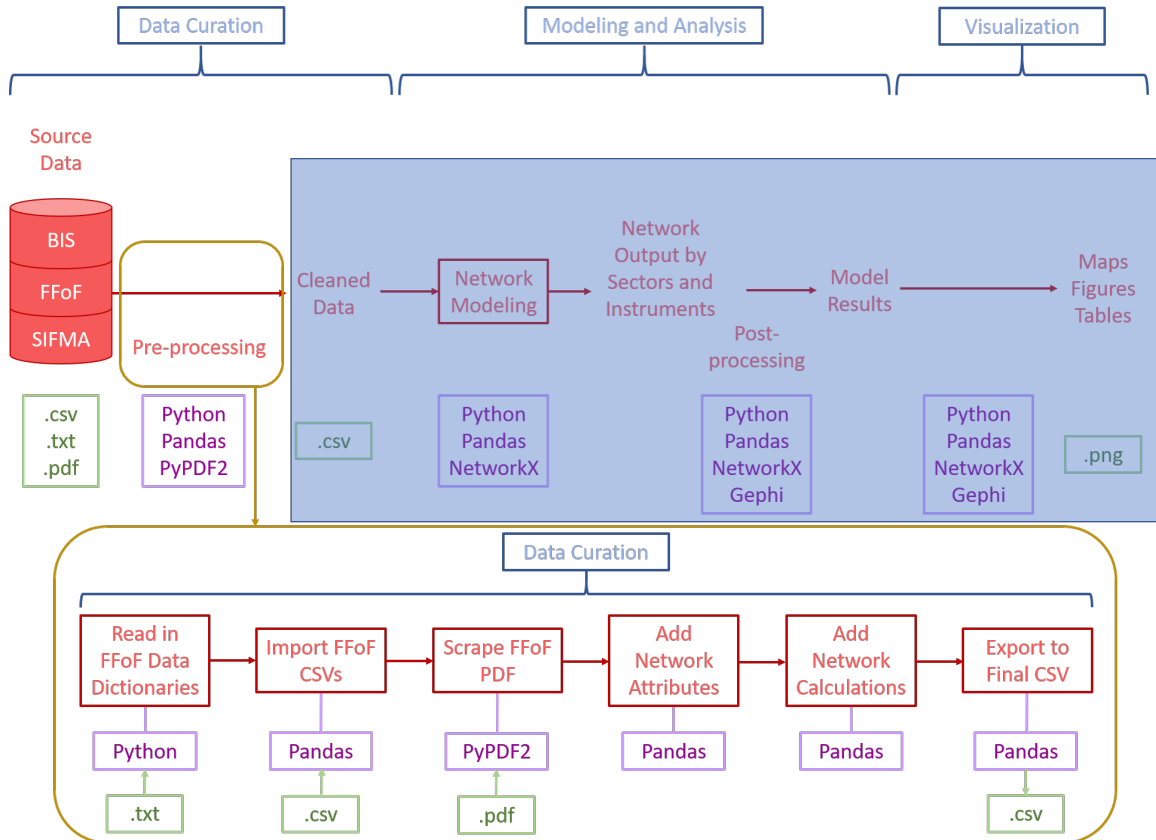


Figure 3.4. Pre-processing workflow. The first three steps are repeated 35 times (once for every level table) before the initial dataframe is created.

Initial Dataframe

After downloading the necessary files (i.e., the FFoF PDF and its corresponding .csv and .txt files), we begin by reading in a table's data dictionary from the table's .txt file line-by-line and storing all the information therein. Next, we read in the .csv file corresponding to that data dictionary, linking the information in the .txt and .csv files by using the unique identifier found in both. Finally, we use the identifiers to determine the page on which the table is found in the PDF; that page is then scraped to determine whether an identifier is at the lowest categorization tier and tagged as such. We then combine and temporarily store

this information. We repeat the process for every table and combine the temporarily stored information from each table into a Pandas dataframe.

Attributes for Building a Network

At this stage, we store all the data from the various FFoF file formats in a single Pandas dataframe. We create a separate dataframe from the initial dataframe by selecting only those entries we previously tagged as being at the lowest categorization tier to avoid overcounting. We then add several attributes to our newly-created dataframe to aid in construction of a network.

- ***Abbreviated Names:*** The sector and money names in the FFoF are long enough that creating a network visualization with the full names makes the visualization illegible. We assign abbreviated names to each sector (e.g., S-01) and money (e.g., M-01) and populate them in a new column of the dataframe to improve the legibility of the visualizations we create later.
- ***Nodes:*** Nodes are essential components of a network, and we use existing information in the dataframe to create the network nodes explicitly. We add two new columns to the dataframe to denote the beginning and ending nodes for a network arc. Since money flows from an asset holder to a liability holder, the asset holder is always the beginning primary node, while the liability holder is always the ending primary node. Since the classification relates to money, money forms intermediate nodes. Therefore, one arc is directed from a sector as an asset holder of a given money to the intermediate node for that money. A second arc is then directed from the intermediate node to the sector which is the liability holder for that money. Note that monies frequently flow through intermediaries, namely operators. Furthermore, the FFoF data show who holds those monies at the date of publication. The sectors holding those monies differ over time.
- ***Arcs:*** Arcs are the other essential components of a network. We add a new column to the dataframe to create the network arcs. We take the newly-created beginning and ending node columns and concatenate them in a tuple representing a network arc. Each tuple is of the form (S-01, M-01) or (M-01, S-01).
- ***Top Sectors:*** If the user so desires, they may add a new column to the dataframe which denotes whether a sector is one of the biggest sectors in a money and classification

group. The column tags sectors which comprise the top percent of a group; the user designates this percentage. The user can then use the tag to select only those rows of the dataframe which contain the top sectors.

Calculations

We perform two calculations and store them in the dataframe for every money and classification grouping. For example, all sectors holding residential mortgages as a liability form one group, while all sectors holding Treasury securities as an asset form another. We recognize there are many ways to group the data to gain different perspectives. We begin with this grouping for the purposes of this thesis.

- **Relative Weight:** We determine each sector's holding within its group as a percentage of the overall group's. We use the relative weight in visualizations to aid in quickly seeing those sectors which are of the most importance for a given money; we accomplish this by using the relative weights to shade the directed arcs in the network. We multiply every percentage by a factor of five to make all shadings easier to see.
- **Cumulative Sum:** We calculate the cumulative sum at each entry within a group. The cumulative sum is necessary for the implementation of selecting the top sectors by group described above.

3.3 Final Data Set Characteristics

After we add the network attributes and calculations, we create multiple .csv files. The primary file contains the following information from the processed dataframe.

- **From Node:** The beginning node of an arc. This is either a sector or a money abbreviation. It is the complement of the entry in the "To Node" column. For example, if a sector is in the From Node column, a money is in the "To Node" column.
- **To Node:** The ending node of an arc. This is either a sector or a money abbreviation. It is the complement of the entry in the "From Node" column.
- **Arc:** A tuple combining the "From Node" and "To Node" columns.
- **Instrument:** The form of money that is in either the "From Node" or "To Node" column.

- **Sector:** The sector that is in either the “From Node” or “To Node” column.
- **Asset/Liability:** The classification of the sector’s holding of the money.
- **Amount:** The sector’s actual holding amount of a money, by classification.
- **Instrument Weight:** The calculation of the sector’s percentage of the money and classification grouping to which it belongs, multiplied by five.
- **Cumulative Weight:** The cumulative weight calculation, ordered from the sectors holding the greatest share of the group to the sectors holding the least share of the group.
- **Sector Color:** The color assigned to a sector for visualization purposes.
- **Instrument Color:** The color assigned to a money for visualization purposes.

We also create two other .csv files which contain the legends of the sector and money abbreviations. We do this to avoid recreating the legends by processing the “From Node”, “To Node”, “Instrument”, and “Sector” columns of the primary .csv file.

3.4 Data Validation

As we discuss in Section 3.2.1, the .csv files for every table in the FFoF begin in 1945 and proceed quarterly. As a result, there are nearly 300,000 instances where our code must accurately combine information from the associated FFoF PDF, .txt files containing the FFoF data dictionaries, and the amounts in those .csv files. We validate our code works properly in three ways.

First, the manner in which we construct the code in such a way that the unique identifiers found in each table of the PDF must exactly match the same identifiers found in the .txt and .csv files associated with that table. We also implement a high-level verification in our code which ensures there are the same number of entries in the PDF, .csv, and .txt files. Therefore, we expect our code works as desired.

Second, we verify the code results by randomly spot-checking the entries in the Pandas dataframe we construct against the corresponding entries found in the FFoF PDF. Figure 3.5 illustrates our process with Table L.204 from the FFoF (from Figure 3.3).

Finally, we use the curated dataframe to create a number of network visualizations during our analysis. Some of these visualizations demonstrate a balance of assets and liabilities,

```
In [15]: qa
```

```
Out[15]:
```

	Table	ID	Instrument_Abb.	Year:Quarter	Asset/Liability	Amount
33707	L.204	FL793120005.Q	Checkable Deposits and Currency	2019:Q3	L	4617.755
33708	L.204	FL713120005.Q	Checkable Deposits and Currency	2019:Q3	L	2111.792
33709	L.204	FL713123005.Q	Checkable Deposits and Currency	2019:Q3	L	382.663
33710	L.204	FL713124005.Q	Checkable Deposits and Currency	2019:Q3	L	31.814
33711	L.204	FL713122605.Q	Checkable Deposits and Currency	2019:Q3	L	5.216
33712	L.204	FL713125005.Q	Checkable Deposits and Currency	2019:Q3	L	1692.099
33713	L.204	FL763127005.Q	Checkable Deposits and Currency	2019:Q3	L	2072.372
33714	L.204	FL763123005.Q	Checkable Deposits and Currency	2019:Q3	L	1.979
33715	L.204	FL763122605.Q	Checkable Deposits and Currency	2019:Q3	L	80.939
33716	L.204	FL763129205.Q	Checkable Deposits and Currency	2019:Q3	L	1989.454
33717	L.204	FL753127005.Q	Checkable Deposits and Currency	2019:Q3	L	194.180
33718	L.204	FL753122603.Q	Checkable Deposits and Currency	2019:Q3	L	71.983

Figure 3.5. Sample selection from our Pandas dataframe. Note the table, identifiers, classification (i.e., whether the money is a liability or asset), the quarter, and the amount match with the Q3 column found in Figure 3.3.

broken down by money. If the assets and liabilities do not balance, we inspect further and correct the underlying problem, if one exists. Such a problem may not exist because, for some monies, the FFoF lists discrepancies between assets and liabilities. Since the visualizations do not incorporate the discrepancies, they will necessarily show a slight imbalance.

3.5 Summary

The FFoF data require extensive cleaning and processing to combine them into a single format ready for follow-on work. Since pre-processing is time-intensive, we write the final dataframe to .csv files, which completes the Data Curation stage in Figure 3.1. We then reimport the .csv files in a separate Python file, where the overall analytical workflow continues. We create a network and its visualizations in that workflow, which we discuss further in Chapter 4.

CHAPTER 4:

Analysis of a Market Map

Having previously described the techniques necessary to curate data for entities and relationships in the financial system, this chapter focuses on the network’s key features, network analysis, and vulnerabilities in the observed network.

4.1 Key Network Features

We build a network of relationships between sectors and monies using NetworkX, a Python programming language package meant for creating and analyzing networks (Hagberg et al. 2008). The network consists of 42 sectors as primary nodes and 25 monies as intermediate nodes, and 430 arcs connecting them, grouped into the categories in Figure 4.1. We call sectors primary nodes and monies intermediate nodes because capital flows between sectors through monies.

Sectors 42 primary nodes	Banks 6 primary nodes 66 arcs	Financial Business 5 primary nodes 53 arcs	Government 3 primary nodes 46 arcs	GSEs 2 primary nodes 21 arcs	Households 1 primary node 27 arcs
	Insurance Companies 3 primary nodes 45 arcs	Investment Funds 8 primary nodes 52 arcs	Non-Financial Business 5 primary nodes 63 arcs	Rest of the World 1 primary node 27 arcs	Retirement Funds 8 primary nodes 29 arcs
Monies 25 intermediate nodes	Cash 3 intermediate nodes 41 arcs	Direct Investment 1 intermediate node 17 arcs	Equities 2 intermediate nodes 24 arcs	Fixed Income Securities 4 intermediate nodes 107 arcs	Insurance 1 intermediate node 8 arcs
	Investment Fund Shares 2 intermediate nodes 22 arcs	Loans 8 intermediate nodes 140 arcs	Retirement Instruments 1 intermediate node 8 arcs	Short-Term Fixed Income Securities 2 intermediate nodes 53 arcs	Taxes Payable 1 intermediate node 9 arcs

Figure 4.1. Sector names, identifiers, and holding amounts by category. We abbreviate sector and category names with identifiers to promote legibility in figures. We group and color sectors into similar categories by category. The listed amounts are the total assets and liabilities for each category.

Figure 4.2 lists each of the sectors, their abbreviated identifiers, and the total amount invested in and by each sector, whereas Figure 4.3 lists each of the monies, their abbreviated identifiers, and the total amount sectors invest in and borrow of those monies as of December 12, 2019, the most recent release of the FFoF data as of this writing (Board of Governors of the Federal Reserve System 2019).

ID	Sector	Category ID	Category	Amount Invested (\$ trillions)
S-01 S-02 S-03 S-04 S-05 S-06	Banks in U.S.-affiliated areas Credit unions Foreign banking offices in the U.S. Foreign banking offices in the U.S., including IBFs U.S.-chartered depository institutions U.S.-chartered depository institutions, including IBFs	SC-01	Banks	\$34.8
S-07 S-08 S-09 S-10 S-11	Corporate equities finance Finance companies Issuers of asset-backed securities Other financial business Security brokers and dealers	SC-02	Financial Business	\$21.9
S-12 S-13	Agency and GSE-backed mortgage pools Government-sponsored enterprises	SC-03	GSEs	\$18.5
S-14 S-15 S-16	Federal government Monetary authority State and local governments, excluding employee retirement funds	SC-04	Government	\$35.3
S-17	Households and nonprofit organizations	SC-05	Households	\$107.0
S-18 S-19 S-20	Life insurance companies Life insurance companies, general accounts Property-casualty insurance companies	SC-06	Insurance Companies	\$16.2
S-21 S-22 S-23 S-24 S-25 S-26 S-27 S-28	Closed-end funds Equity real estate investment trusts Exchange-traded funds Money market funds Mortgage real estate investment trusts Mutual funds Private pension funds Real estate investment trusts	SC-07	Investment Funds	\$62.3
S-29 S-30 S-31 S-32 S-33	Corporate farm business Holding companies Noncorporate farm business Nonfinancial corporate business Nonfinancial noncorporate business	SC-08	Non-Financial Business	\$89.0
S-34	Rest of the world	SC-09	Rest of the world	\$55.8
S-35 S-36 S-37 S-38 S-39 S-40 S-41 S-42	Federal government defined benefit retirement funds Federal government defined contribution retirement funds Federal government retirement funds Private defined benefit pension funds Private defined contribution pension funds Private pension funds, including 403(b) plans State and local government employee defined benefit retirement funds State and local government employee retirement funds	SC-10	Retirement Funds	\$23.5

Figure 4.2. Sector names, identifiers, and holding amounts by category. We abbreviate sector and category names with identifiers to promote legibility in figures. We group and color sectors into similar categories. The listed amounts are the total assets and liabilities for each category.

ID	Instrument	Category ID	Category	Amount (\$ trillions)
M-01	Checkable Deposits and Currency	MC-01	Cash	\$35.5
M-02	Time and Savings Deposits			
M-03	U.S. Deposits in Foreign Countries			
M-04	Direct Investment	MC-02	Direct Investment	\$32.2
M-05	Corporate Equities	MC-03	Equities	\$126.2
M-06	Proprietors' Equity in Noncorporate Business			
M-07	Agency- and GSE-Backed Securities	MC-04	Fixed Income Securities	\$92.6
M-08	Corporate and Foreign Bonds			
M-09	Municipal Securities			
M-10	Treasury Securities			
M-11	Life Insurance Reserves	MC-05	Insurance	\$4.5
M-12	Money Market Fund Shares	MC-06	Investment Fund Shares	\$40.3
M-13	Mutual Fund Shares			
M-14	Commercial Mortgages	MC-07	Loans	\$65.9
M-15	Consumer Credit			
M-16	Depository Institution Loans Not Elsewhere Classified			
M-17	Farm Mortgages			
M-18	Home Mortgages			
M-19	Multifamily Residential Mortgages			
M-20	Other Loans and Advances			
M-21	Trade Credit			
M-22	Pension Entitlements	MC-08	Retirement Instruments	\$55.1
M-23	Federal Funds and Security Repurchase Agreements	MC-09	Short-Term Fixed Income Securities	\$11.3
M-24	Open Market Paper			
M-25	Taxes Payable by Businesses	MC-10	Taxes Payable	\$0.9

Figure 4.3. Money names, identifiers, and amounts invested. We abbreviate money and category names with identifiers to promote legibility in visualizations. We group monies into similar categories and color them by category. The listed amounts are the assets invested in each category (since assets and liabilities generally balance in the FFOF data).

Arcs connect sectors and monies. An arc begins at a sector node and is directed to a money node if the sector holds that money as an asset, while an arc begins at a money node and is directed to a sector node if the sector holds that money as a liability. The FFoF data show monies broken down by sector holdings or vice-versa; as such, arcs are not directed sector-to-sector or money-to-money. The network contains 430 of a possible 2,100 sector-to-money and money-to-sector arcs. The remaining possible connections do not exist in the FFoF data because for those combinations of sectors and monies, the sectors do not hold those monies as either an asset or a liability.

This network of 67 nodes and 430 arcs is not large by modern computational standards, but nonetheless, understanding its key structural features is not easy. The NetworkX package includes support for visualizing graphs using different layout schemes, which we consider as a starting point to “see” what we can in terms of structure and now investigate as part of our network analysis.

4.2 Network Analysis

Because we have two types of nodes and the FFoF data precludes sector-to-sector or money-to-money arcs, a bipartite graph may be useful. We begin with aggregation by category, as this can help to eliminate noise caused by the large number of arcs relative to the number of nodes, and illustrate the resulting bipartite graph in Figure 4.4. In this figure and subsequent visualizations, arcs are colored according to a sector’s relative weight within a grouping of a money and a holding classification, with darker shades reflecting a greater relative weight. An arc’s thickness is determined by a scaled version of a sector’s actual holding amount of a given money.

Figure 4.4 provides limited insight. We are able to observe only that category MC-10 (red box) is sparsely connected with low holding amounts. This suggests the need for greater granularity, despite the possibility of noise.

Figure 4.5 shows the financial network with nodes arranged in a simple circle and colored by sector and money as defined in Figure 4.2 and Figure 4.3. As a result of the increased granularity in Figure 4.5 over Figure 4.4, we see sectors S-32 and S-33 (tan box) are the most significant sectors in the Non-Financial Business category by connections and holdings. We also see sector S-17 (teal box) is dominant amongst all sectors in terms of connections and

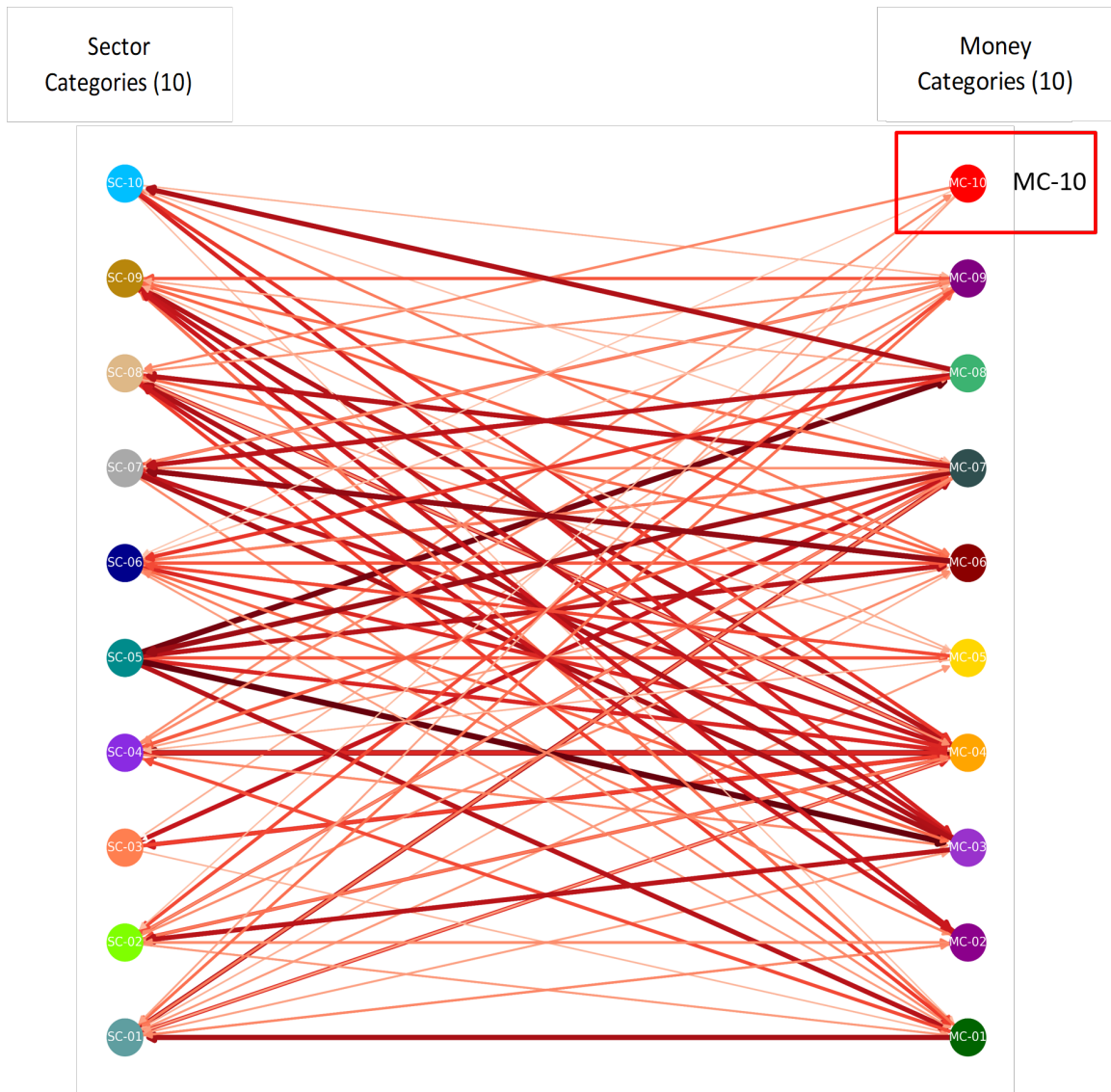


Figure 4.4. We display the full network as a bipartite graph, with sectors and monies grouped into their respective categories to reduce noise. However, we are only able to see that one category, MC-10 (red box), is sparsely connected, indicating the need for more granularity.

holding amounts. However, it is difficult to discern the most significant monies.

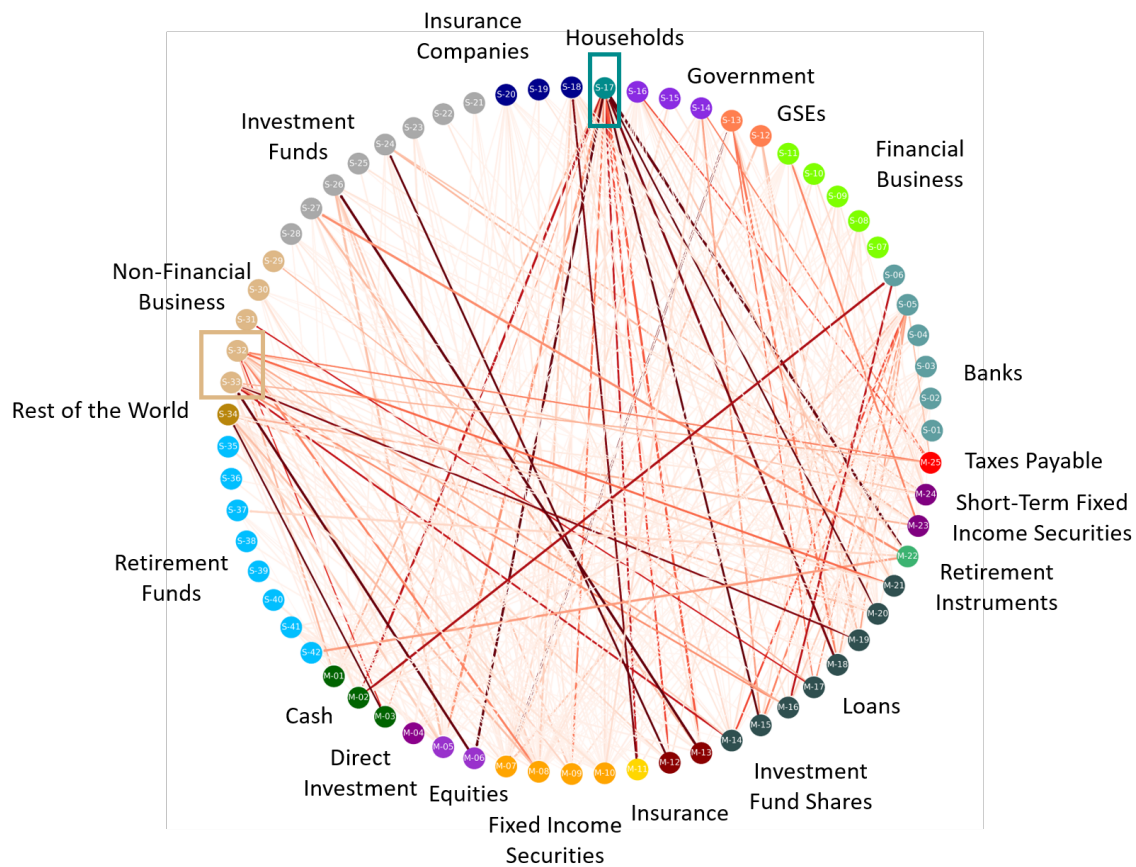


Figure 4.5. Circular layout of financial network. Sector and money nodes are presented along the upper and lower halves of the circle, respectively, and are colored according to Figure 4.2 and Figure 4.3. We see sectors S-32 and S-33 (tan box) are the most significant sectors in the Non-Financial Business category by connections and holdings. We also see sector S-17 (teal box) is dominant amongst all sectors in terms of connections and holding amounts. However, it is difficult to discern the most significant monies.

The insights we gain due to the increased granularity in Figure 4.5 suggests it may be beneficial to reproduce a bipartite graph of the full network, presented in Figure 4.6. Here, we now see monies that are densely connected or have significant investments or liabilities, such as M-06 (purple box), M-12, and M-13 (red box). We also see M-15 and M-18 have the largest investments and liabilities amongst monies in the Loans category.

In general, connections from sectors to monies are not symmetric with connections from monies to sectors. Figure 4.7 (showing liabilities in red) and Figure 4.8 (showing assets in blue) illustrate the differences using two node incidence matrices, where sectors holding greater amounts of a money are shaded more darkly if the amount they hold of a given money is greater than a certain percentage of other sectors (e.g., it is shaded most darkly if the amount held is greater than the amounts held by 90% of other sectors). We gain several new insights from the visualizations.

First, we observe a much greater dispersion of assets than liabilities. In Figure 4.7, we see that sectors in the Non-Financial Business category (tan oval) have both widely dispersed liabilities and hold large amounts of those liabilities relative to other sectors, augmenting the insight gained from Figure 4.5. We also note that sectors in the Retirement Funds category hold very few liabilities (in some instances, none at all). This speaks to another potential aggregation problem directly in the FFoF data, as sectors in Retirement Funds should hold more monies as liabilities owed to households (sector S-17).

Finally, we compare Figure 4.8 with Figures 4.5 and 4.7. In Figure 4.8, we observe sectors in the Fixed Income Securities category are much more widely dispersed than any other sectors and hold significant assets. The significance of those assets did not appear in Figures 4.5 or 4.6 because they are so widely dispersed; indeed, there are more sectors in the darkest shades (top 50%) of every money in the Fixed Income Securities category than there are for any other money outside that category, a point that illustrates both the dispersion and amounts held in the category. In comparing Figure 4.8 with Figure 4.7, we see also see a much greater dispersion of assets and a heavier concentration of liabilities (since assets and liabilities balance).

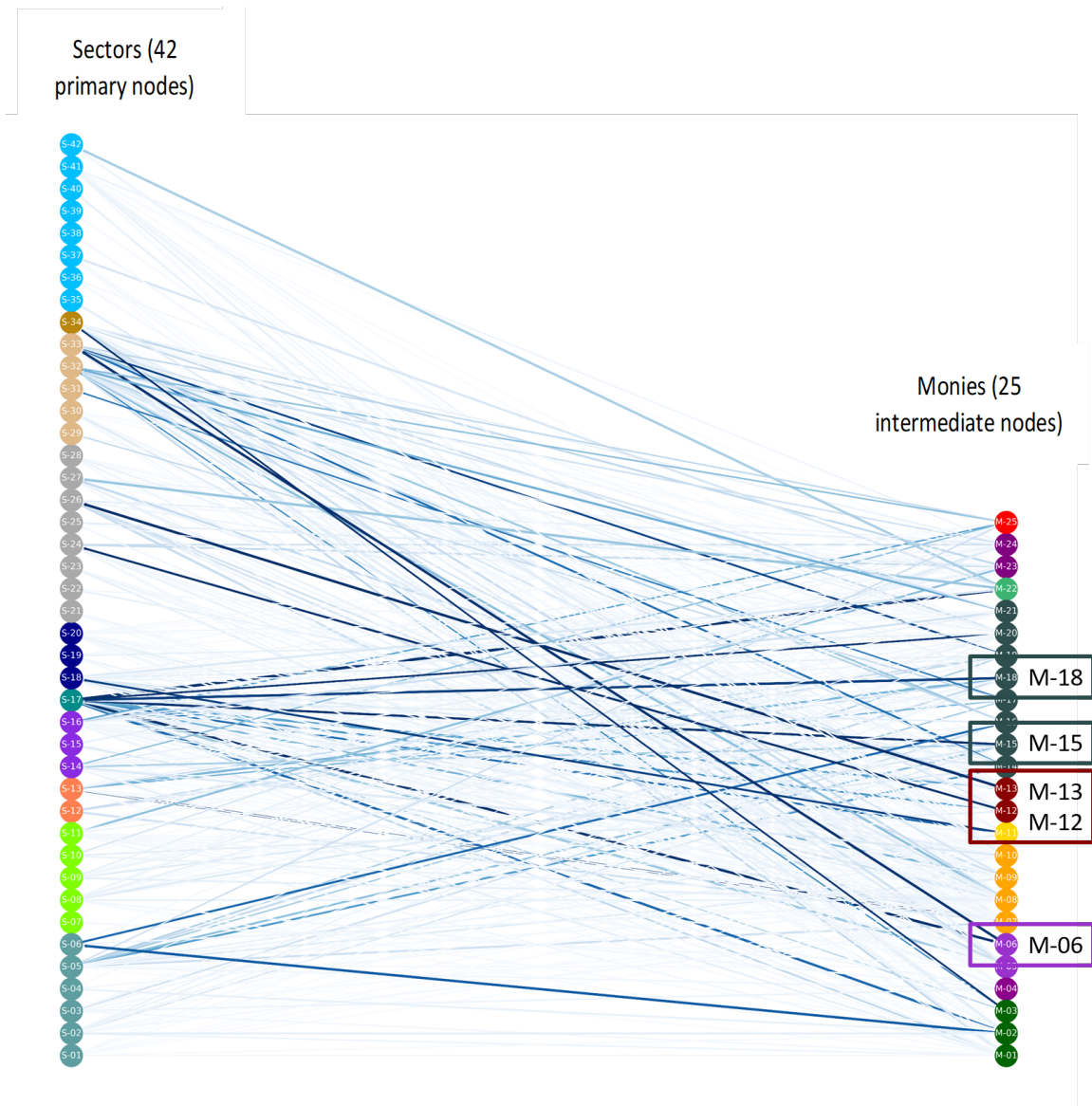


Figure 4.6. Bipartite layout of financial network. Sector nodes are on the left, with monies on the right. The graph confirms the observations made about important sectors in Figure 4.5. We can also see monies with large investment and borrowing amounts, such as M-06 (purple box), M-12, and M-13 (red box). We also see M-15 and M-18 (dark teal boxes) are the most important monies in the Loans category.

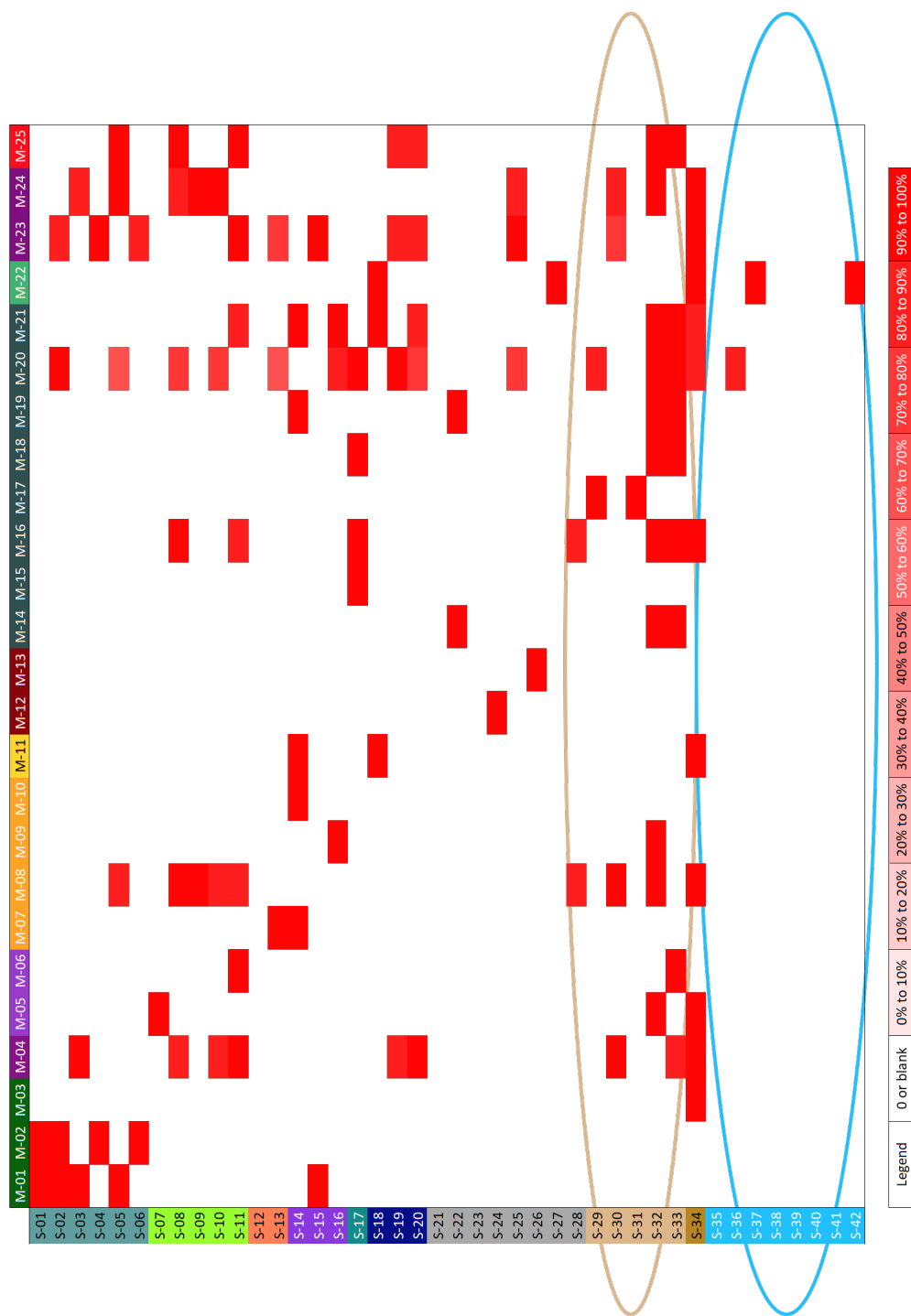


Figure 4.7. Node incidence matrix for liabilities. Most non-zero cells are shaded darkly because there are very few sectors holding each money as a liability. We see that sectors in the Non-Financial Business category (tan oval) have both widely dispersed liabilities and hold large amounts of those liabilities relative to other sectors. By contrast, the Retirement Funds category (blue oval) holds very few liabilities, with some sectors holding none at all.

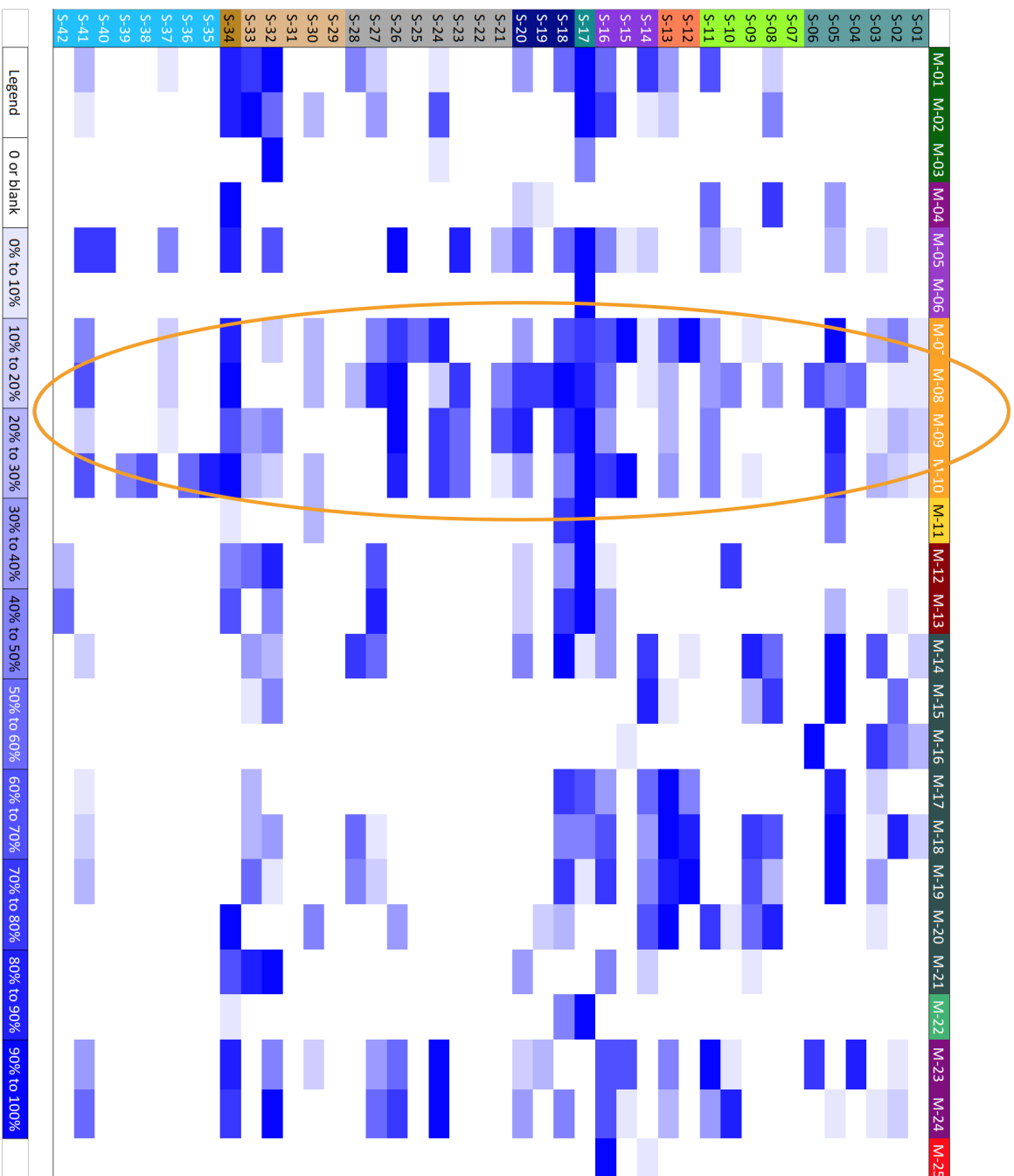


Figure 4.8. Node incidence matrix for assets. We note that the Fixed Income Securities category (orange oval) is much more widely dispersed than other category and holds significant assets. The significance of those assets did not appear in Figures 4.5 or 4.6 because they are so widely dispersed.

Our visualization in Figure 4.4 is insufficiently granular for us to gain insights into the network, but Figures 4.5, 4.6, 4.7, and 4.8 reveal some of its key features. The following sections produce further insights by investigating node rankings, connectivity and density, and node centrality.

4.2.1 Node Rankings

We now rank the nodes by their in- and out-degree. A sector's in-degree represents the number of monies it borrows, while its out-degree represents the number of monies in which it invests. By contrast, a money's in-degree represents the number of sectors investing in that money, while its out-degree indicates the number of sectors borrowing that money. Figures 4.9 and 4.10 rank sectors and monies, respectively. In a few instances in Figure 4.10, the amount invested does not equal the amount borrowed. The FFoF tracks these discrepancies as a separate line item and notes they are the result of "measurement errors, missing information, and incompatibilities among data sources" (Board of Governors of the Federal Reserve System 2019). Since the discrepancies are not attributed to any one sector, we do not include them in the calculations for any ranking table.

By ranking nodes in this way, we gain further insight into concentration of capital and node connectivity. A high in- and out-degree for a sector indicates high dispersion of liabilities and assets, respectively, while for a money it indicates a high number of investors and borrowers. In Figures 4.9 and 4.10, sectors and monies with both a high in-degree and high out-degree are presented in yellow. Sectors and monies with a high in-degree and low out-degree or vice-versa are presented in green. The combination of a high in- and out-degree indicates wide dispersion, while a high in- and low out-degree (or vice-versa) indicates either predominantly one type of activity (i.e., investing or borrowing), a concentration of capital, or both. These differing combinations reveal the different roles sectors and monies play in the financial system and therefore the different avenues for attacking them.

We observe in Figure 4.9 that there are four sectors (in yellow) that have large in- and out-degree: S-11, S-32, S-33, and S-34. The sectors' connections are also widely dispersed across multiple categories, exposing them to a wide variety of monies and rendering them more vulnerable to attack. We make a similar observation for monies M-08 and M-23 in Figure 4.10.

In-Degree	Liability Amount (in millions)	Sector	Out-Degree	Asset Amount (\$ trillions)
4	\$1.4	S-02	10	\$1.3
3	\$0.6	S-03	11	\$0.9
5	\$2.9	S-05	15	\$10.9
6	\$1.1	S-08	9	\$1.5
8	\$3.2	S-11	10	\$2.9
3	\$7.0	S-13	13	\$6.8
5	\$19.3	S-14	13	\$2.3
3	\$4.1	S-16	17	\$3.1
7	\$16.3	S-17	20	\$89.6
3	\$5.9	S-18	16	\$6.8
5	\$0.4	S-20	13	\$2.1
1	\$10.5	S-27	11	\$5.6
12	\$50.5	S-32	17	\$14.4
9	\$6.7	S-33	11	\$2.6
11	\$22.7	S-34	16	\$33.1
0	\$0	S-41	13	\$3.9

Figure 4.9. The largest sectors ranked by in-degree and out-degree, with their corresponding liabilities and investments. Sectors highlighted in light yellow have high in- and out-degree. Sectors highlighted in green have either a low in-degree and high out-degree or vice-versa. Sectors highlighted in orange have a high out-degree and disproportionately large assets.

By contrast, we see in Figure 4.9 sectors with low in-degree (in green): S-27 and S-41. Sector S-27 has in-degree one but a large liability amount, indicating a concentration of capital. In Figure 4.10, there are six monies with low in- or out-degree. In particular, M-05 has low out-degree as well as the largest amount borrowed, again indicating a concentration of capital.

Finally, we observe the importance of sector S-17. In Figure 4.9, we see S-17 has the largest out-degree and asset holdings.

A crisis of confidence caused in a well-connected node would cause significant harm since the damage would readily spread. A concentration of capital is vulnerable due to the

In-Degree	Amount Invested (\$ trillions)	Ranking*	Money	Out-Degree	Amount Borrowed (\$ trillions)	Ranking*
7	\$16.1	SI	M-04	10	\$16.1	LO
18	\$49.6	LI	M-05	3	\$49.6	SO
22	\$9.5	LI	M-07	3	\$9.3	SO
25	\$14.2	LI	M-08	9	\$13.9	LO
19	\$4.1	LI	M-09	3	\$3.8	SO
25	\$18.9	LI	M-10	1	\$18.9	SO
17	\$11.1	LI	M-18	3	\$11.1	SO
15	\$4.1	-	M-20	16	\$4.1	LO
17	\$4.7	LI	M-23	11	\$4.5	LO
16	\$1.1	LI	M-24	9	\$1.1	LO

*	LI – Large In	LO – Large Out	SI – Small In	SO – Small Out
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Figure 4.10. The largest monies ranked by in-degree and out-degree, with their corresponding investments and liabilities. Monies highlighted in light yellow have high in- and out-degree. Monies highlighted in green have either a low in-degree and high out-degree or vice-versa.

high reward (from an attacker's perspective) that concentration represents, as well as the possibility there are relatively few points of failure. In an instance where a node is well-connected and has a concentration of capital (as with sector S-17), the node may vulnerable to multiple modes of attack.

4.2.2 Network Connectivity and Density

We now discuss measures of connectivity and density in the network. We begin by presenting summary statistics in Figure 4.11. Note the network density is calculated using only sector-to-money or money-to-sector arcs since other arcs are precluded by the structure of the FFoF data.

Connectivity Statistics	
Average Node Degree	6.42
Network Density*	0.20
Diameter (U)	5
Average Shortest Path Length	3.85
Longest Shortest Path Length	5
Number of Longest Paths	177
Shortest Shortest Path Length	3
Number of Shortest Paths	684
Strongly Connected?	No
Weakly Connected?	Yes

* - Considering only sector-to-money or money-to-sector arcs.

Figure 4.11. Network connectivity and density statistics. Note that since the network is only weakly connected, the diameter is only defined if the network is undirected (U).

We draw the following conclusions from the statistics in Figure 4.11.

- The network contains more than 20% of all possible arcs, but the density is approximate because the FFoF data do not provide sufficient granularity to determine one sector's claims on another sector. It is possible a sector which lends a certain money could be directly connected to every sector which borrows that money, some sectors which borrow that money, or just one sector which borrows that money. Therefore, the network may be more or less dense than the current network indicates.
- From a mathematical perspective, the network is not strongly connected, so it is not possible to begin from an arbitrary node in the directed network and reach any other node.

- The network is weakly connected, so it is possible to begin from an arbitrary node and reach any other node if the network is undirected (i.e., it contains edges rather than arcs). While direction is important in considering how money flows in the network, it is just as important to know that such connections simply exist given the integral relationship between lenders and borrowers. The existence of those connections provides a path for damage from a financial warfare attack to be transmitted quickly and directly from lender to borrower or vice-versa.
- If we consider only paths that begin and end with a primary sector node, the diameter of the undirected network is five. Since there are no sector-to-sector or money-to-money edges in the undirected network, two of the nodes on any of the longest shortest paths are money nodes. Therefore, sector nodes are separated by at most one other sector node.
- Furthermore, nearly 80% of all paths beginning and ending with a primary sector node are of length three, indicating a potential direct connection via at least one money between those sectors. Therefore, the damage caused by the failure of a given sector or money is likely to spread rapidly throughout the network.
- There are 861 possible paths between sectors in the directed network, of which 565 (65.6%) exist. All the shortest paths have sectors which are either directly connected or separated by one sector. The conclusion we draw about damage spreading rapidly does not change when we consider direction.

We demonstrate the importance of our point-in-time analysis in Figure 4.12, which presents holdings in the Equities category for Q3 2019. Sectors holding a given money as an asset and a liability are on the left and the right, respectively. Figures 4.12 provide an alternate view of density contextualized by the “flow” of investment from an asset to a liability holder. They also allow for immediate identification of the largest lenders and borrowers within a money category (and by individual money). For example, we quickly see sectors S-17 and S-26 (teal boxes) alone comprise more than half of M-05, the largest money in the category.

Sectors S-17 and S-26 are Households and Non-Profit Organizations and Mutual Funds, respectively, and money M-06 is Corporate Equities. Since households own most of the capital invested in mutual funds, we see they invest more than half the capital in Corporate Equities, one of the two biggest markets through which businesses raise funds. Furthermore, sector S-17 provides significant capital to S-33 (tan box) as the only investor

in M-06. We conclude the borrowing sectors are heavily dependent upon S-17, and any attack which damages S-17 would immediately and directly impact those sectors as well. Figure 4.12 focuses on the Equities category, but similar diagrams focusing on the other money categories may yield similar insights.

4.2.3 Network Centrality

We conclude our network analysis with a brief discussion on centrality, illustrated in Figure 4.13. A node's eigenvector centrality is determined both by how well-connected the node is and how well-connected the nodes to which it is connected are.

We observe in Figure 4.13 that the five most central money nodes are M-08, M-10, M-07, M-01, and M-20. The five most central sector nodes are S-32, S-16, S-17, S-06, and S-18. All but M-01 and S-06 are noted in Figures 4.10 and 4.9. Therefore, Figure 4.13 confirms our previous insights while also suggesting other nodes are of significance which we have not already observed. Because eigenvector centrality measures how well-connected a node is by considering the node's and its neighbors' connections, it provides insight into the network's most important nodes, particularly when we combine that view with the magnitude of the assets and liabilities of those nodes.

Our analysis has demonstrated several important points. First, top-level aggregation is too coarse to gain much insight, whereas we are able to observe important network features with greater granularity. Our visualizations also yield different insights, which suggests there may be other network features that would be revealed by different visualizations. Finally, those insights include different dominant sectors and monies from a dispersion and concentration perspective, which provide different opportunities for attack which we discuss in our concluding section.

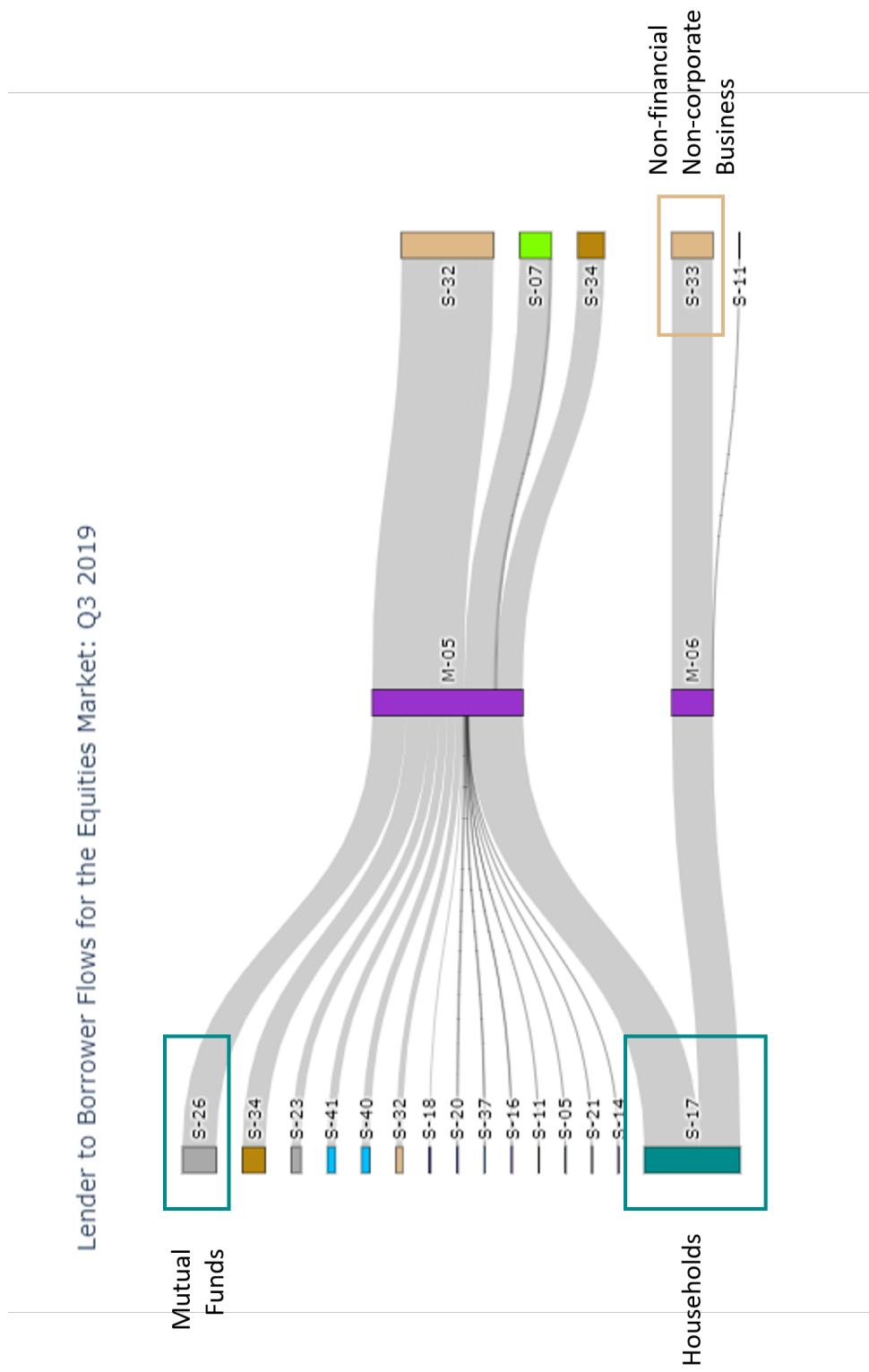


Figure 4.12. Equities category, Q3 2019. Seventeen sectors hold one of the two monies in the Equities category. Prominent characteristics include the largest investors (S-17, S-26, and S-34) and the relative sparsity of borrowers (three total).

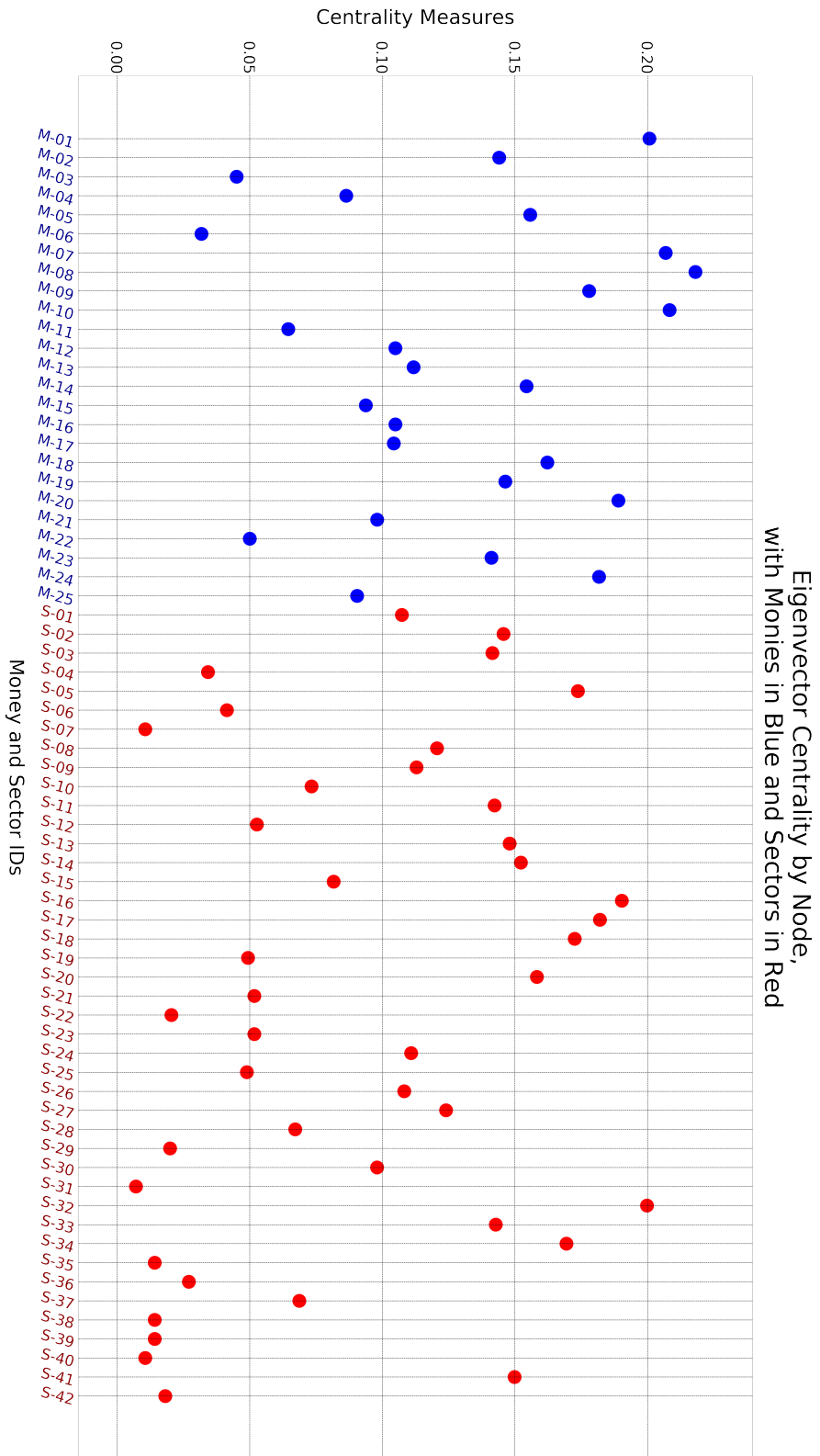


Figure 4.13. Scatterplot of eigenvector centrality by node. Since eigenvector centrality provides a measure both of how well-connected a node is and how well-connected the node's connections are, it yields insight into the overall effect the node has on the network.

4.3 Vulnerability Analysis

Our analysis of network structure is important in that it helps to reveal key features relevant to the vulnerability of the financial network. Building on the discussion in Section 2.5, there are several broad vulnerabilities we consider.

Single points of failure. We first consider areas of the network where there are few players. A reliance on a few critical nodes or connectors creates a vulnerability because an attack on them may disable a key activity in the financial system. As a result, highly concentrated nodes offer high rewards (from an attacker’s perspective), either because of the impact that a loss of a large amount of capital or borrowing would have or because the nodes might represent single points of failure. In general, examples of highly concentrated nodes include players such as large asset managers (e.g., Fidelity, Vanguard, Blackrock) and operators in trade processing (DTCC). Imagine seeing a zeroed-out retirement account and the impact this could have on the entire investment market — as happened with Fidelity in February 2020 (Malito 2020). In our financial network, we observe several highly concentrated nodes, including M-05 (Corporate Equities), S-17 (Households and nonprofit organizations), and S-33 (Nonfinancial noncorporate business).

Places of widespread impact. Next, we consider those players who participate broadly throughout the financial system — that is, they are highly dispersed. These participants represent a vulnerability because an attack on them could resonate throughout the financial system. For example, an attack which causes a crisis of confidence would become a contagion in the financial system due to the high connectivity of such nodes. This kind of attack could make players afraid to invest in or borrow monies or lend to or borrow from sectors critical to the functioning of the financial system. For example, many players invested in collateralized mortgage obligations (CMOs) prior to the 2008 financial crisis. At that time, CMOs were a highly dispersed money whose failure immediately impacted the players investing in it, as well as players and monies that were effectively collateral damage (Kagan 2020) — especially individuals and families who lost their homes. Examples of highly connected participants are individuals and/or households who rely on their ability to access funds and complete financial transactions, amongst other activities. We observe several highly dispersed nodes throughout our analysis, including M-08 (Corporate and foreign bonds), S-32 (Nonfinancial corporate business), and S-17 (Households and nonprofit organizations).

Some nodes in our financial network represent both high dispersion and a high concentration of capital, which renders them vulnerable to multiple methods of attack. Sectors S-17 (Households and nonprofit organizations), S-32 (Nonfinancial corporate business), and S-33 (Nonfinancial noncorporate business) are examples.

We also observe some nodes are important across most or all of the visualizations we employ, which suggests they are systemically important and therefore represent the greatest vulnerabilities. Those nodes include S-17 (Households and Non-Profit Organizations), S-32 (Non-Financial Corporate Business), S-33 (Non-Financial Non-Corporate Business), and M-08 (Corporate and Foreign Bonds).

Robustness. We define players and monies as robust if they have a system of checks and balances, regulatory oversight, a high degree of standardized interaction, low complexity, and fast transaction or settlement speed. If players or monies lack one of these features, it is easier to attack them and possibly more than once if the attacker cannot be identified because of a lack of robustness. Examples are complex monies, such as some financially engineered instruments, some payment platforms, and crypto-currencies.

Rapid growth. We examine players and monies demonstrating rapid growth in the network from one period to the next; that growth may be in holdings (in the case of players and monies) or the number of participants (in the case of monies). Areas in the network experiencing rapid growth may require meaningful expertise or suggest increased stress to other players and/or monies as they gain relative importance in the financial system. Examples in the current markets are financial technology (FinTech) payment platforms, financial engineered instruments such as some collateralized loan obligations (CLOs), leveraged loan products and exchange-traded funds (ETFs), crypto-currencies, and exchanges, among others. The growth of CMOs, the market for which was largest in 2007 (less than a year before the financial crisis began in earnest), is just one example (Kagan 2020).

The vulnerabilities we discuss here are by no means exhaustive but are meant to be illustrative. More importantly, they are determined only from a point-in-time analysis. The ability to generate the network, its features, and its visualizations quickly allows us to consider a final perspective of temporal changes between two quarters, which we discuss in Chapter 5.

CHAPTER 5:

Changes in Maps Over Time

Our techniques for automating the process of collecting, curating, and integrating different sources of financial data into a market map are important, in that they allow us to apply various network analysis tools for understanding key structural features and potential vulnerabilities. However, the connectivity of the financial system — as defined in this thesis by the holdings of different sectors — can change over time. This feature makes the financial system different from many other critical infrastructures whose connectivity is physical (e.g., roads) and tends to change very slowly, if at all. A point-in-time analysis can reveal insights into the financial system’s vulnerabilities, but analysis of an outdated map could lead to false conclusions about the system’s vulnerabilities. Because players, operators, and monies can quickly and regularly reshuffle their relationships in the financial system, it is also critical to analyze how the system *changes*.

The dynamic nature of the financial system makes it somewhat unique in its structure relative to those other infrastructure systems and presents different challenges for studying its vulnerabilities. Fortunately, the techniques in this thesis for producing market maps quickly and consistently opens the door for an entirely new type of analysis related to these changes in the structure of the financial system.

In the following sections, we present examples to demonstrate the changing nature of the financial system and how its vulnerabilities may evolve over time.

5.1 Changes in the Financial System Over Time

By comparing the structure of the financial network at different time periods, we get a sense of the way in which capital has moved. Figure 5.1 contrasts holdings in the Loans category for the fourth quarter of 2008 and third quarter of 2019 (the most recently available data), respectively.

We observe three important points in Figure 5.1. First, the number of lending sectors has increased while the number of borrowing sectors has decreased between Q4 2008 to Q3

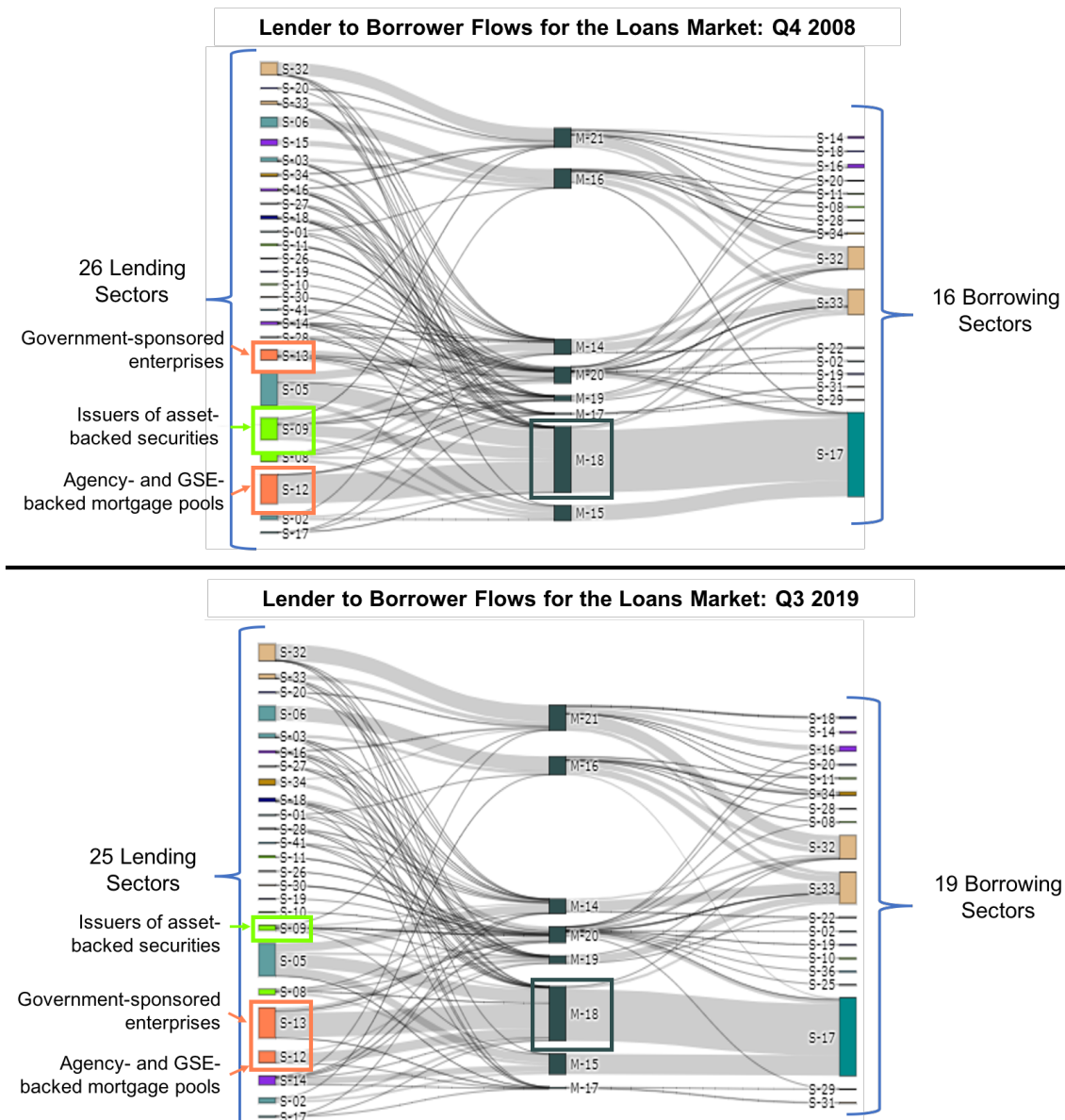


Figure 5.1. Loans category for Q4 2008 (top) and Q3 2019 (bottom). The relative size of sector S-09 decreases significantly from 2008 to 2019 (green box), whereas the relative size of sectors S-12 and S-13 (orange boxes) in their holdings of money M-18 (dark green box) are swapped over this period. There is an increase in the number of borrowing sectors and a decrease in the number of lending sectors from 2008 to 2019.

2019. Therefore, different sectors represent vulnerabilities in the Loans market and may be impacted by an attack on it.

Second, some sectors have increased or decreased their asset holdings. We see that sector S-13 (first orange box) has substantially increased its asset holdings. Conversely, sectors S-09 (green box) and S-12 (second orange box) have substantially decreased their asset holdings.

Finally, we can see some sectors investing in new monies, eliminating their holdings of monies, or filling in for other sectors over time. In Q4 2008, sector S-12 was the largest asset holder of money M-18 (dark green box), while sector S-13 held no assets of M-18. By Q3 2019, S-13 is now the largest asset holder of M-18, while S-12's holdings of M-18 is dramatically reduced. This suggests that, over time, S-13 gradually took over the role once filled by S-12.

Furthermore, there are significant changes in the Loans category between Q4 2008 and Q3 2019. Figure 5.2 demonstrates three different values for sectors holding monies in the Loans category. The first value is the actual increase in a sector's holding of assets (in blue) or liabilities (in red) between Q4 2008 and Q3 2019. The second value is the percentage increase that change represents relative to the sector's holding of that money in Q4 2008. The third value shows how much that increase represented as a percentage of the assets or liabilities held of that money by all sectors in Q4 2008. Every sector in Figure 5.2 increased its holdings in Q3 2019 over Q4 2008 by at least 100%. Most strikingly, we observe that S-13's assets of M-18 increase approximately \$4.5 trillion, which represents a 1,047% increase in S-13's assets of M-18 and more than 40% of the assets of M-18 held by all sectors in Q4 2008.

Figure 5.3 also demonstrates three different values for sectors holding monies in the Loans category. The first value is the actual decrease in a sector's holding of assets (in blue) or liabilities (in red) between Q4 2008 and Q3 2019. The second value is the percentage decrease that change represents relative to the sector's holding of that money in Q4 2008. The third value shows how much that increase represented as a percentage of the assets or liabilities held of that money by all sectors in Q4 2008. Every sector in Figure 5.3 decreased its holdings in Q3 2019 over Q4 2008 by at least 50%. We see sector S-09's assets of M-18 decrease more than \$1.5 trillion (from more than \$2 trillion to around \$1 trillion), which is

a 78% reduction in S-09's assets of M-18 and nearly 14% of the assets of M-18 held by all sectors in Q4 2008. We also see that sector S-15 completely eliminated its assets of money M-16, and similarly, sector S-09 reduced its assets of money M-15 by more than 97%, which demonstrates the disappearance of a sector from a market. Figures 5.2 and 5.3 give insight into the vulnerabilities surrounding rapidly growing sectors and monies we discuss in Section 4.3, as well as the sectors that have become relatively less important over time.

We gain more information about the actual changes in a sector's holding amounts of a money with diagrams such as Figure 5.4. Figure 5.4 shows compares sectors S-09, S-12, and S-13. The figure includes those sectors' eigenvector centralities, amounts borrowed or invested in money M-18, and in- and out-degree for Q4 2008 and Q3 2019 compared side-by-side. With such diagrams, we can immediately see how the sector's overall connectivity in the network (as measured by the eigenvector centrality, in-degree, and out-degree) and borrowing and lending activities have changed between the two time periods. For example, we see that Issuers of Asset-backed Securities (sector S-09) had significant lending and borrowing activities in money M-18 in Q4 2008 but had nearly eliminated all such activities by Q3 2019. Conversely, we see the opposite is true of Government-sponsored Enterprises (sector S-13).

We also note that the in-degree, out-degree, and eigenvector centrality of the sectors do not change. In the case of S-13, we observe in Figure 5.1 the sector did not invest in M-18 in Q4 2008 but does as of Q3 2019. Since the connectivity of S-13 does not change, the sector's assets and liabilities must have shifted. Moreover, the growth of a sector's assets and liabilities while its connectivity remains static indicates a concentration of capital in an area where such concentration may not have previously existed.

Notable Increases (\$ Billions) in Loans Category From Q4 2008 to Q3 2019

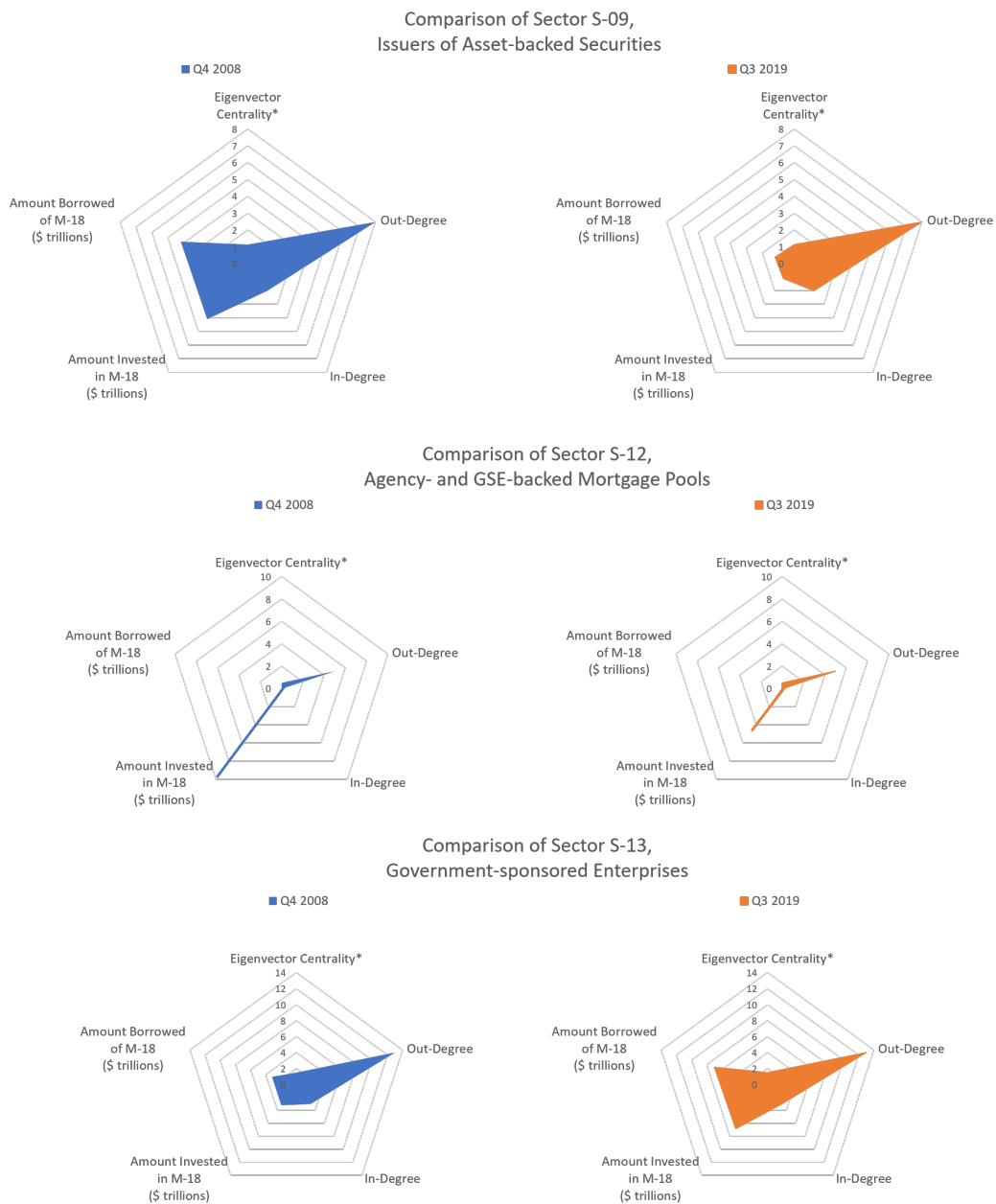
	S-02	S-03	S-10	S-12	S-13	S-14	S-17	S-18	S-19	S-20	S-25	S-28	S-29	S-30	S-32	S-33	S-34	S-36
M-14		\$39.3 B 136% 1.6% of M-14								\$16.0 B 333% 0.6% of M-14		\$145.4 B 380% 5.9% of M-14						
M-15	\$247.5 B 103% 9.4% of M-15					\$1181.9 B 902% 44.7% of M-15												
M-16	\$48.3 B 152% 1.8% of M-16						\$218.9 B 82% 8.8% of M-16										\$414.0 B no prior value 16.6% of M-16	
M-17							\$9.6 B 1451% 7.4% of M-17						\$40.4 B 152% 31.3% of M-17					
M-18								\$25.4 B 296% 0.2% of M-18										
M-19		\$6.2 B 138% 0.7% of M-19		\$279.3 B 316% 32.9% of M-19				\$93.3 B 174% 11.0% of M-19				\$6.4 B 144% 0.7% of M-19						
M-20		\$2.4 B no prior value 0.1% of M-20				\$111.4 108% 2.7% of M-20			\$47.60 124% 1.1% of M-20		\$8.4 B no prior value 0.2% of M-20		\$6.2 B 107% 0.1% of M-20	\$119.5 B 1879% 2.9% of M-20	\$568.6 248% 13.7% of M-20		\$568.6 B 248% 13.7% of M-20	\$23.1 B no prior value 2.3% of M-20
M-21																\$409.1 B 107% 11.5% of M-21		

Figure 5.2. We present sectors and their holdings in monies for both assets (blue) and liabilities (red). The first entry in each cell shows the actual increase in holdings. The second entry shows the percent increase relative to what the sector held in Q4 2008. The third entry shows how much that increase represented as a percentage of the assets or liabilities held of that money by all sectors in Q4 2008. Every sector presented increased its holdings by at least 100%.

Notable Decreases (\$ Billions) in Loans Category From Q4 2008 to Q3 2019

	S-01	S-03	S-08	S-09	S-11	S-12	S-15	S-17	S-32
M-14	\$10.3 B 53% 0.4% of M-14		\$35.6 B 58% 1.4% of M-14						
M-15				\$595.1 B 98% 23.3% of M-15				\$60.9 B 68% 2.3% of M-15	
M-16					\$131.7 B 51% 5.3% of M-16		\$289.8 B 100% 10.8% of M-16		
M-17						\$3.3 B 69% 2.5% of M-17			
M-18		\$5.6 B 67% 0.0% of M-18	\$313.9 B 78% 2.8% of M-18	\$1,553.8 B 78% 13.8% of M-18		\$2,798.4 B 58% 24.9% of M-18		\$52.6 B 51% 0.5% of M-18	
M-19				\$74.1 B 63% 8.7% of M-19					\$19.0 B 52% 0.2% of M-19
M-21				\$63.1 B 66% 1.9% of M-21					

Figure 5.3. We present sectors and their holdings in monies for both assets (blue) and liabilities (red). The first entry in each cell shows the actual decrease in holdings. The second entry shows the percent decrease relative to what the sector held in Q4 2008. The third entry shows how much that decrease represented as a percentage of the assets or liabilities held of that money by all sectors in Q4 2008. Every sector presented decreased its holdings by at least 50%.



* - Scaled by factor of 10 for visibility

Figure 5.4. Radar plots for sectors S-09, S-12, and S-13 in Q4 2008 and Q3 2019. We observe the connectivity of each sector remains the same, while their assets and liabilities of money M-18 change substantially.

5.2 Further Vulnerabilities

We now discuss potential vulnerabilities we identify using the temporal views in Section 5.1 and the importance of analyzing differences in the financial system over time by contrasting those views with our discussion in Section 4.3.

In Section 5.1, we observe the growing importance of sector S-13 to money M-18 and the Loans category generally, along with the relative decline of sectors S-09 and S-12. In Q4 2008, sectors S-09 and S-12 represented potential vulnerabilities. Indeed, S-09 is Issuers of Asset-backed Securities, and S-12 is Agency- and GSE-backed Mortgage Pools, both of which represented vulnerabilities in the financial system because of their exposures to residential mortgages — or money M-18. Since Q4 2008, these sectors have largely been supplanted by S-13, or Government-sponsored enterprises. Other potential vulnerabilities we identify by combining the analysis and visualizations in Chapter 4 with temporal views.

In Section 4.3, we identify several monies and sectors that represent potential vulnerabilities, including monies M-05 and M-08 and sectors S-17, S-32, and S-33. By contrast, we identify S-13 as a potential vulnerability due to its increased importance to money M-18 and the Loans market generally. We note that S-13 did not appear in any of the point-in-time visualizations or analyses as an important node. Therefore, the temporal view we discuss in this chapter identifies a potential vulnerability which would be missed if one were to rely upon only a point-in-time analysis.

5.3 Opportunities for Additional Analyses

The automation of creating the network enables the fast comparison of changes across two periods in time. We propose several views for future work.

Obtain a snapshot of sector assets and liabilities. By comparing snapshots, we can determine how a sector’s investing and borrowing behavior has changed over time.

Establish a significance threshold for each money and sector. By establishing a significance threshold, we can identify new sectors as they enter the market for a given money. Conversely, we can also identify sectors that are no longer significant. We can do the same for monies to identify emerging and disappearing markets.

Identify holding concentration. We can see growing concentrations of assets or liabilities by comparing map iterations. Concentrated holdings represent few or single points of failure.

Identify dispersion. Conversely, we can compare map iterations to see greater dispersion of holdings (i.e., sectors investing their capital in or borrowing more monies than other sectors) or of sectors (i.e., more sectors investing in or borrowing a given money). Dispersion in either form can support the financial system by having more sectors available to support the market for a money should another sector fail, but it can also expose more sectors to damage from the failure of another sector or a money.

Investigate maturity profiles of monies. The connections between sectors represented by monies last for different amounts of time. For example, an equity trade connects two sectors for one day (the time it takes to settle the trade), while mortgages can last for up to 30 years. Comparing map iterations by money can provide insight into how behavior in markets differ.

Analyze turnover. The FFoF data we use to build the network in this thesis show end-of-quarter holdings. As such, those data do not reflect *turnover*, or how often a money is traded. For example, some players hold relatively few assets or liabilities at any one time but trade monies very frequently, such as algorithmic traders. These players would appear to have relatively little market exposure using a point-in-time analysis. However, due to constant changes in the market, their frequent trading substantially increases their overall exposure, and as such, the activities of these players are ideally suited for a temporal analysis that cannot be captured by the FFoF level data we use.

These examples are not exhaustive but provide several views that can reveal vulnerabilities that would not otherwise be captured by a point-in-time analysis. Therefore, it is important to consider multiple network perspectives.

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CHAPTER 6:

Summary and Follow-On Work

We conclude by summarizing the work we present in this thesis, describing the limitations on our efforts, and recommendations for follow-on work to improve the network approach we employ.

6.1 Summary of Current Efforts

Warfare is continually evolving, and modern warfare incorporates hybrid elements that often target important infrastructure to achieve military goals. The financial system is a critical infrastructure sector; we rely upon it, whether explicitly or implicitly, for nearly every facet of our daily lives. It supports other critical infrastructure sectors and U.S. national security.

Recognizing that our adversaries have considered financial warfare as a means to leverage U.S. infrastructure vulnerabilities to overcome their disadvantages in traditional warfare, we work to create a network representation of the financial system, which provides us with a different perspective on potential vulnerabilities.

We begin to create the network by first establishing a set of criteria for its underlying data. The data must be comprehensive, in that they cover the most significant monies, players, and operators; manageable, in that they balance granularity with the ability to aggregate the data; reliable, in that they come from a trusted organization; regular, in that they are published with enough frequency to allow for timely network creation and analysis; and confirmable, in that data from multiple sources largely agree. We identify several sources which meet most or all of these criteria, such as the Federal Reserve, BIS, and SIFMA. We focus the efforts of this thesis on the Federal Reserve's FFoF to lay a foundation that will be built upon by future work.

We specifically focus on the FFoF's level data, which are end-of-quarter sector holding amounts of each money tracked in the FFoF. We develop a computational workflow to import the data, which are contained in three file formats: a PDF release of the overall quarterly FFoF report, comma-separated value (.csv) files containing holding amounts for

the current and historical quarters, and plain-text (.txt) files containing the data dictionary for each table of level data. We then programmatically clean the data and organize it into a format suitable for our analysis. The curated data set is a critical end-product; we use it to create a network that we analyze and visualize to identify key features.

We analyze the network in two general ways. First, we look at the network at a specific point in time. Using this approach, we identify sectors and monies that are either highly connected, have large concentrations of capital, or both and which therefore represent vulnerabilities in the financial system. These include monies M-05 and M-08 and sectors S-17, S-32, and S-33.

Second, we compare the network at multiple points in time, which we are able to do as a result of our work to automate the network's creation. By comparing network iterations, we identify sectors that enter or exit certain markets or which become prominent in them and therefore to the financial system as a whole. For example, we identify sector S-13 as becoming a prominent lender of money M-18 in Q3 2019 where it had not been active at all in Q4 2008, while sectors S-09 and S-12 greatly reduce their lending activity for M-18.

6.2 Limitations

Our work is limited in several ways, some of which are general and others specific to our use of the FFoF.

6.2.1 General Limitations

The financial system is global in nature. Our work creates a network only of the U.S. financial system. Therefore, we are unable to determine the ramifications that the failure of a component of the global financial system would have on the U.S. financial system.

There are a number of activities for which it is not possible to obtain data. Some examples include financial transactions carried out via cryptocurrencies (which are designed for anonymity); so-called “dark pools,” which are owned by financial institutions and which allow investors to engage in financial transactions privately; and criminal activity. These and other enterprises likely account for significant financial transactions that cannot be captured by a network.

The U.S. financial system is different from other financial systems around the world in key ways. For example, eighty percent of capital in the U.S. is raised via markets, while the remaining 20% is borrowed from banks; the converse is true in Europe. Therefore, lessons learned from a network of the U.S. financial system do not necessarily translate over to other financial systems.

The network we create focuses on monies and players; it does not include operators. Operators are critical to the stable functioning of the financial system. As such, they represent another possible avenue for financial warfare attacks.

Finally, our network analysis is oriented only from a defensive perspective of the U.S. financial system. We might gain different insights by taking an offensive approach towards the U.S. financial system.

6.2.2 FFoF Limitations

The Federal Reserve meets our criteria as a reliable source. However, there are limitations associated with our use of its data.

Although the FFoF contains data on many significant monies and players, there are several it does not, especially derivatives. As such, our network cannot capture the impact of those missing monies and players.

We use data from the level tables of the FFoF. Using the level data, we obtain both an end-of-quarter snapshot of a sector's holding amounts of the monies tracked in the FFoF as well as temporal changes by comparing data from different quarters. However, the FFoF contains data on overall trading amounts; these differ significantly from level amounts, as they also capture fluctuations in the price of a money and trading volumes. Therefore, we could gain further insight by using different types of data, either from the FFoF or other sources.

None of the tables in the FFoF are sufficiently granular to allow us to calculate the claims of one sector directly upon another. As such, we cannot determine which sectors are directly connected via one another and must use their connections via mutual monies as a proxy.

The FFoF is published quarterly. In some instances, this is too infrequent to allow timely

analysis. For example, during the 2008 financial crisis, the failure of key financial institutions and the crisis of confidence that precipitated a drop in the prices of certain monies unfolded over approximately two weeks.

Because we do not use data outside the FFoF, we are unable to reconcile our findings from an outside perspective.

6.3 Future Work

There are several avenues for future work to improve upon the foundation we establish in thesis.

The most immediate area for improvement is to add in more data on the U.S. financial system. Doing so addresses many of the limitations on our current work:

- We can improve upon the quarterly frequency with which the network is currently generated.
- We can include more monies and players to assess other potential vulnerabilities.
- We can capture the importance of operators to the financial system, as well as those which constitute potential vulnerabilities.
- We can improve the granularity with which we are able to analyze the network.
- We can reconcile data from multiple sources.

In the long-term, it will be useful to add in global data to construct networks of the financial systems of other countries and to create a network of the global financial system. Doing so would provide a view of how the U.S. would be affected by failures of components of the global system or yield offensive rather than defensive insights, such as how an adversary might indirectly attack the U.S. by directly attacking another entity intimately connected to the U.S.

As the fidelity and accuracy of these network maps improves, it will become possible to apply other analytical tools tailored for use on networks, such as Attacker-Defender models (e.g., Brown et al. 2006). We expect that the application of such tools will provide even more insight into this timely and important problem.

APPENDIX A:

Key Elements of the Financial System

This Appendix briefly describes elements of the financial system and their activities. They are important for understanding the operations of and relationships between financial system components and therefore constitute areas of potential vulnerability. While the list is meant to encompass major elements and activities, it is not exhaustive due to the extensive and changing nature of the financial system. More detailed information on money, players, and operators can be found in Appendix B.

Payment and settlement systems enable the efficient transfer of money for completing (i.e., settling) transactions. They act as intermediaries between a buyer and seller to minimize the risk that one of the parties does not honor their obligation. Examples include FedWire, Clearing House Interbank Payments System (CHIPS), and stock exchanges.

Some organizations are responsible for the secure storage of information concerning financial transactions, and the electronic systems those organizations use may be susceptible to compromise. Examples of these organizations include the DTCC, line entry at banks, pension funds, asset managers, and Social Security. Individuals are particularly vulnerable with respect to these systems, as their deposits, borrowings, or other investments are typically line entry items.

Some monies are of greater relative importance than others from the perspective that they connect large numbers of players; the failure of such monies can therefore have a widespread effect. An example, CLOs, helps to explain the concept. This form of money is a derivative since it derives its value from underlying assets (i.e., loans made by banks). CLOs are then split into tranches, which are groups or features of the underlying loans that create an expected level of investor risk. These tranches are sold to investors. Therefore, CLOs connect multiple borrowers, investors, and operators (those which create the CLOs). Other examples include ETFs, hedge funds, and stocks in the S&P 500.

Financial firms are organizations that comprise players and operators beyond those which provide payment and settlement services. Examples include stock exchanges, such as the

Nasdaq and S&P 500; financial service providers, such as SWIFT, banks, and mortgage companies; and regulators, such as the Federal Reserve Board (FRB) and Securities and Exchange Commission (SEC).

Generally, liquidity reflects the ease and speed with which money can be bought, sold, or otherwise traded. For example, currency is often very liquid, while real estate is relatively illiquid. Here, we refer to liquidity as money which is highly liquid. Beyond currency, examples include money market funds, checking accounts, equities of large capitalization companies, treasuries, and many derivatives.

Risk transfer or return shifts various types of financial risk (e.g., stock market or default risk) from the primary party facing the risk to a secondary party. The secondary party receives a premium for taking on the risk, while the primary party is protected if the risk is realized. While insurance is a common form of risk transfer, there are other forms, such as derivatives, which may be used either to hedge (i.e., protect) against risk to minimize losses or to take on greater risk to maximize rewards.

Widespread market behaviors can amplify normal cyclical changes in financial markets (i.e., they are procyclical). Examples include risk management techniques that rely upon common statistical approaches — e.g., Value at Risk (VaR) and Modern Portfolio Theory (MPT), both of which are widely used by portfolio managers (Harper 2019; McClure 2019) — and algorithmic trading driven by machine learning techniques.

Blockchain-based activities, first proposed by two computer scientists in 1991 (Haber and Stornetta 1990), began to see widespread use with the advent of cryptocurrencies (e.g., Bitcoin). Many industries are implementing blockchain technologies. In particular, the financial services industry is beginning to use them to speed up and anonymize contract settlements to save money (Kelly 2016; Hackett 2016; Fortney 2019).

Other emerging activities are beginning to bypass or fill the roles held by traditional financial service companies, such as borrowing (whether from fundraising or lending) and payment processing. Crowdfunding platforms, such as Kickstarter and GoFundMe, allow users either to circumvent or to engage in new forms of borrowing; users have raised more than \$9 billion since the inception of those platforms in 2009 and 2010, respectively. GoFundMe users alone raise approximately \$140 million per month (Nguyen 2019; Harris 2017; Monroe

2019). Peer-to-peer lending websites, such as LendingClub, allow a person or group of people to lend to a borrower and therefore directly replace traditional lending sources (e.g., banks). From LendingClub's inception in 2007 through the third quarter of 2019, users have lent more than \$40 billion (LendingClub 2019). New peer-to-peer payment platforms, such as Venmo, allow a person to send money directly to another person. Venmo users sent more than \$19 billion in the fourth quarter of 2018, with the total value of peer-to-peer transactions estimated to be \$156 billion that year (Eckstein 2019). These examples are relatively new, but it is important to recognize that emerging activities like them have the potential to change fundamental aspects of the structure of the financial system.

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APPENDIX B:

Abbreviated Dictionary of the Financial System

As defined in this thesis, participants in the financial system fall into one of three general categories: players, operators, and monies. For purposes of convenience, we include the following working definitions. Unless otherwise noted, we adopt definitions as presented in Investopedia (2020).

The entries are presented alphabetically, with a note on whether the entry is for a player, operator, or money. In the case of monies, we also note to which market (equities, fixed-income, or other) that money belongs. The equities markets deal with equity securities in a business; that is, the participant owns a share of that business and therefore has equity in it. The fixed-income markets deal with various forms of debt securities, from which the participant receives fixed income of some sort, usually in the form of interest.

Agency- and GSE-Backed Securities (money, fixed-income market). These monies include securities issued by certain federal agencies, government-sponsored enterprises, and agency- and GSE-backed mortgage pools (Board of Governors of the Federal Reserve System 2019). Most of the securities are mortgage-backed securities (MBSs), a security collateralized by a grouping of mortgages and that provides periodic payments, which are determined by a share of the principal and interest payments of the underlying mortgages.

Brokerages (operator). A brokerage, or brokerage company, connects two parties for various financial transactions. For example, a brokerage may connect a buyer and seller for a security (e.g., stocks or bonds), a borrower with a bank (e.g., for a mortgage), or assist clients in finding insurance. Some brokerages also provide financial advice, while others provide a platform which allows individual investors to buy and sell securities.

Checkable Deposits and Currency (money, other markets). These monies primarily include variations of demand deposit accounts and currency not held by the Treasury. A demand deposit account is an account held with a banking institution which can be drawn upon without notifying the institution — i.e., on demand. This is effectively a checking

account, or an account against which checks may be written without notice to the institution, hence a checkable deposit.

Clearing Houses (operator). A clearing house acts as a middleman for a buyer and seller in a financial transaction and ensures the transaction takes place according to terms previously agreed upon by the buyer and seller—that is, they ensure funds or assets change hands as agreed. There is inherently risk in every financial transaction: the seller might not produce the asset being sold, or the buyer might not have sufficient funds, in which case either party might attempt to renege on the transaction. A clearing house takes on the risk of the transaction to ensure the buyer receives the asset and the seller receives the funds, thereby providing stability in those transactions. The clearing house does this by temporarily taking on the position opposite both the buyer and seller; that is, they are the counterparty to the buyer (where the seller was when the transaction began) and the counterparty to the seller (where the buyer was when the transaction began), a process known as offsetting. Some clearing houses ensure payments and assets are exchanged (e.g., funds for a security), while others ensure transfer of funds (i.e., a check clears when cashed). Clearing houses also ensure trades are settled, i.e., assets and funds are delivered to the appropriate party. Examples of the first type of clearing house include those of each financial exchange, while an example of the second type is FedACH, an ACH managed by the federal government.

DTCC. The DTCC is one of the world's largest financial services organizations. It integrates the functions of its subsidiaries, including clearing houses and a central securities depository. Because the central securities depository holds a large volume of assets, it allows transactions to be cleared by the clearing houses by crediting and debiting accounts rather than requiring the actual transfer of the securities between parties, thereby allowing transactions to be completed much more quickly and efficiently.

Commercial Banks (operator). Commercial banks are also part of U.S.-chartered depository institutions as a player. From an operator perspective, they provide key financial services, especially to individuals, such as checking and savings accounts, basic investment vehicles (e.g., certificates of deposit), installment credit (e.g., mortgages or car loans), and revolving credit (e.g., credit cards).

Consumer Credit (money, fixed-income market). These monies include loans to individuals in the households sector, not including mortgages. The loans include, for example, credit cards, car loans, and student loans (Board of Governors of the Federal Reserve System 2019).

Corporate and Foreign Bonds (money, fixed-income market). These monies are various debts issued by domestic corporations (financial and non-financial) and foreign organizations (held by domestic entities). These monies focus primarily on bonds, although some others (e.g., notes) are included.

Corporate Equities (money, equities market). These monies include common and preferred shares in both financial and non-financial corporations, including U.S.-held shares of foreign corporations (Board of Governors of the Federal Reserve System 2019).

Custodian Banks (operator). Custodian banks are so-called because their primary purpose is to provide a safe repository for securities — that is, the securities are in the custody of the bank.

Derivatives (money, other markets). A derivative is a financial money based on another asset; the performance of that asset determines the derivative's value (i.e., the value is derived from the asset). Derivatives encompass many types of monies, such as futures and swaps; the latter of these is the means by which risk is traded between financial institutions. Derivatives are not outlined in the FFoF but represent such a large market we include them here, with the gross market value of derivatives estimated to be \$12.7 trillion in 2018, according to the BIS (Maverick 2018).

Direct Investment (money, other markets). These monies include large investments made by domestic entities in foreign entities or vice-versa; an investment is considered large if it constitutes at least a 10% stake in the foreign entity (Board of Governors of the Federal Reserve System 2019).

Electronic Funds Transferrers (operator). Electronic funds transferrers are organizations which facilitate the transfer of funds between two bank accounts. It is a broad category which includes ACH organizations, wire transfer organizations (e.g., FedWire), and payment companies (e.g., Visa) (Kenton 2019a).

Federal Funds and Security Repurchase Agreements (money, fixed-income market).

These monies include federal funds, which are used by U.S.-chartered depository institutions to meet a minimum reserve balance with the Federal Reserve, and security repurchase agreements, also known as repos. In a repo, a buyer purchases a security from the seller, with a promise from the seller to repurchase the security a short time later; the “interest” on this “loan” is the difference in the sale and repurchase prices. The security underpinning the repo serves as collateral (Reiff 2020).

Federal Government (player). This sector includes all parts of the U.S. federal government as delineated in the federal budget. The liabilities for the federal government are smaller than the overall public debt because they do not include treasury securities held within the federal government itself — that is, the federal government effectively owing itself money (Board of Governors of the Federal Reserve System 2019).

Financial Communications (operator). A financial communications firm provides a secure network for financial institutions, especially banks, to exchange financial information. SWIFT is the world’s primary provider of this network; it is used to place payment orders between institutions (Schwartz 2016).

Financial Corporations (player). In the FFoF data, this is broken out in only one location, under Corporate Equities. It is not, however, described as its own sector in the FFoF; the data indicate that public and closely-held financial corporations are included, though (Board of Governors of the Federal Reserve System 2019).

Financial Exchanges (operator). A financial exchange provides a marketplace where monies can be traded. There are several exchanges in the U.S. The two largest and most well-known are the New York Stock Exchange and the NASDAQ.

Fund Shares (money, equities market). These monies include shares of money market and mutual funds. They may be redeemed by the owner at any time (Board of Governors of the Federal Reserve System 2019).

Funds (player). In the FFoF, this sector includes mutual funds, money market funds, closed-end funds, and exchange-traded funds (Board of Governors of the Federal Reserve System 2019); note that we include other funds for definition purposes. Generally speaking,

these funds are professionally-run investing organizations which pool capital from investors and invest that capital in a variety of assets to provide steady growth while reducing risk. The capital is raised by selling shares in the fund.

Closed-End Fund. A closed-end fund differs from a mutual fund in that new shares are not issued after an initial offering.

Exchange-Traded Fund. An exchange-traded fund invests similarly to a mutual fund, but its shares are bought and sold on a stock exchange; therefore, the trade is made with another investor, rather than with the fund directly.

Hedge Fund. A hedge fund is an investing organization run by professional managers. Hedge funds gather capital to invest generally from wealthier individuals and are subject to less regulation than other types of funds (e.g., mutual funds); as such, they are allowed greater discretion in their investment strategies. They may also borrow capital to invest in a wider array of monies (called leveraging) to minimize (or hedge against) risk.

Money Market Fund. A money market fund is a mutual fund which invests only in high-credit, short-term securities.

Mutual Fund. Mutual funds are the largest of the four types of funds in this sector. Here, they are open-ended mutual funds (meaning the fund can continue to issue shares over time and therefore raise more capital to invest) which report to the Investment Company Institute, an association representing regulated funds. Shares in a mutual fund are bought from and sold to the fund itself.

Private Equity Fund. Similar to a hedge fund, a private equity fund pools capital for investment from wealthier individuals (as well as some institutional investors). However, private equity funds are so called because they generally focus on long-term investments in private companies; the capital being invested often is used either to provide financing to young companies or to enable poorly managed companies an opportunity to improve (Maverick 2020).

Government-Sponsored Enterprises (player). This sector includes financial service corporations established by Congress with the goal of increasing accessibility to credit. The organizations comprising the sector are the Federal Home Loan Banks, the Federal National Mortgage Association (better known as Fannie Mae), the Federal Home Loan Mortgage Corporation (better known as Freddie Mac), the Federal Agricultural Mortgage Corporation (better known as Farmer Mac), the Farm Credit System, the Financing Corporation, and the Resolution Funding Corporation (Board of Governors of the Federal Reserve System 2019).

Holding Companies (player). This sector includes bank, savings and loan, U.S. intermediate, and securities holding companies, generally with at least \$1 billion in assets (Board of Governors of the Federal Reserve System 2019). A holding company (sometimes known as a parent company) holds enough shares of at least one other company (a subsidiary) to have a controlling interest in that subsidiary; the holding company generally does not run the subsidiary's operations and may or may have its own business operations.

Households (player). This sector includes individual households and non-profit organizations, such as charities, foundations, and schools. Data provided in the FFoF indicate hedge funds, private equity funds, and personal trusts are also included (Board of Governors of the Federal Reserve System 2019).

Insurance Companies (player). This sector includes both property-casualty and life insurance companies. The sector does not include funds established by individual states to cover their workers' compensation programs (Board of Governors of the Federal Reserve System 2019).

Property-Casualty Insurance Company. A property-casualty insurance company is authorized to write most commonly known types of policies, such as homeowner's (or rental), car, private mortgage (PMI, also known as mortgage guaranty), and other insurances (American Insurance Association 2020).

Life Insurance Companies. A life insurance company is authorized to write policies providing beneficiaries with financial protection in case of death of the insured party; for the FFoF, this includes all legal reserve life insurance companies. A company's

legal reserve is a minimum amount of money from each policy premium which the company must set in reserve to ensure all policies can be paid.

Investment Banks (operator). Investment banks differ from commercial banks in key ways. First, they are not depository institutions. Second, the services they offer are more specialized; these include underwriting large debts (the process of assessing their risk, which in turn determines the return those debts will generate), assisting with large business transactions (e.g., mergers and acquisitions), and facilitating secondary markets for securities by buying those securities when they are first issued and then reselling them to individual investors. Note that many banks have both commercial and investment sides after the repeal of the Glass-Steagall Act in 1999.

Life Insurance Reserves (money, other markets). These monies are funds that life insurance companies have established to pay for claims against their policies.

Loans (money, fixed-income market). These monies encompass two categories: depository institution loans not elsewhere classified (NEC) and other loans and advances. The FFoF report includes two other categories (mortgages and consumer credit), but each is large enough to warrant its own entry. Depository institution loans NEC and other loans and advances primarily include loans which do not fall under mortgages, consumer credit, or open market paper (Board of Governors of the Federal Reserve System 2019).

Market Makers (player and operator). A market maker is both a player and an operator in the financial system; it is typically a firm which has committed to buying and selling securities for certain companies on a financial exchange. The market maker will buy securities from sellers and hold them until a buyer for those securities is available. Because some securities do not trade regularly, this action promotes liquidity in the markets for those securities.

Monetary Authority (player). This sector includes the banks of the Federal Reserve (of which there are 12) and some select U.S. Treasury accounts, which are not included in the Federal Government sector above (Board of Governors of the Federal Reserve System 2019).

Money Market (money, fixed-income market). The money market consists of securities which have short maturities (less than a year). Monies in the money market help participants fund immediate operations, and they are generally considered to be safe investments because they are most often issued by institutions with good credit. These monies are traded over-the-counter (OTC)—that is, they are not traded on an established exchange but are instead traded electronically between participants.

Mortgages (money, fixed-income market). These monies include any loan collateralized by property. They include four sub-categories: home mortgages, for residential properties with one to four residential units; multi-family residential mortgages, for properties with more than four residential units; commercial mortgages, for non-residential properties; and farm mortgages (Board of Governors of the Federal Reserve System 2019).

Municipal Securities (money, fixed-income market). These monies include debts of state and local governments, non-profit organizations, and non-financial corporate businesses. State and local governments issue most municipal securities, and they do so via either general obligation or revenue bonds. The former is backed by the municipality, while the latter is funded by revenue from a specific source, such as a toll road).

Non-Financial Corporate Business (player). This sector includes all private (i.e., not publicly traded), for-profit corporations which do not provide financial services (Board of Governors of the Federal Reserve System 2019). Because incorporation provides many legal benefits, most businesses are corporations.

Non-Financial Non-Corporate Business (player). This sector includes partnerships, sole proprietorships, limited liability companies, and individuals receiving rental income (Board of Governors of the Federal Reserve System 2019).

Limited Liability Company. The term limited liability refers to the idea that, at most, an investor will lose the money he or she currently has invested with a business but is otherwise not liable for the business's debts. A limited liability company combines this feature with the tax treatment of a partnership.

Partnership. A partnership is a small business run by at least two individuals, with a few different arrangements possible which determine control of the business and

assignment of liability. Two key purposes of partnerships are the sharing of liability and preferential tax policies.

Sole Proprietorship. A sole proprietorship is a small business owned by one person who pays income taxes on any profits the business earns.

Pension Entitlements (money, other markets). These monies include liabilities of all retirement funds and annuities established by life insurance companies. They include defined benefit and defined contribution plans, as well as individual retirement accounts (IRAs) (Board of Governors of the Federal Reserve System 2019).

Personal Trust (player). A trust allows a separate manager to maintain assets on behalf of the trust owner. Trusts are often used to reduce estate taxes. The term “personal” here simply means privately held.

Private and Public Pension Funds (player). This sector includes all retirement funds established by organizations in the private sector, state and local governments, and the federal government. The retirement funds include defined benefit and defined contribution plans; in the case of the federal government, the retirement fund does not include the Social Security program (Board of Governors of the Federal Reserve System 2019). Defined benefit plans are usually funded by the employer and pay the employee once he or she has worked for the employer for a minimum time and retired; the amount paid usually depends on how long the employee was with the employer and how much the employee made when he or she retired. Defined contribution plans are usually funded by the employee, with possible contributions from the employer; the employee controls how the money is invested and can begin drawing on the assets after a certain age.

Proprietors’ Equity in Non-Corporate Business (player). These monies include ownership of non-financial non-corporate businesses and non-corporate security brokers and dealers by households (Board of Governors of the Federal Reserve System 2019).

Rest of the World (player). This sector includes any foreign entity engaging in business in the U.S. (Board of Governors of the Federal Reserve System 2019)

Security Brokers and Dealers (player and operator). This sector includes businesses which report to the SEC (Board of Governors of the Federal Reserve System 2019). A broker-dealer completes securities trades for clients (as the broker) or on their own behalf (as a dealer). The sector includes businesses which are brokers, dealers, or both; most are both and are commonly thought of as brokerage firms.

State and Local Governments (player). This sector includes the governments of all 50 states and their municipalities, as well as Washington, D.C. It does not include other U.S. territories, such as Puerto Rico and Guam (Board of Governors of the Federal Reserve System 2019).

Time and Savings Deposits (money, other markets). These monies include time deposits and savings deposits. Time deposits bear interest and mature after a set time, such as a certificate of deposit (Investopedia 2020). Savings deposits bear interest and cannot have checks written against them; instead, they require notice of withdrawal.

Trade Credit (money, other markets). These monies are business-to-business contracts. The contracts indicate the amount a buyer will pay a seller at a future date for goods or services.

Treasury Securities (money, fixed-income markets). These monies include various types of Treasury bills, notes, and bonds; securities from the Federal Financing Bank (an organization established by Congress which assists other federal agencies with borrowing and lending); and Treasury inflation-protected securities, whose principal increases with inflation and therefore protects the principal from loss due to inflation's (Board of Governors of the Federal Reserve System 2019).

Treasury Bill. A treasury bill is a short-term security. It does not provide any interest; however, it provides an investor income because its par value (for which it is redeemed upon maturity) is greater than its purchase price.

Treasury Bond. A treasury bond is similar to a treasury note but has a longer maturity (greater than 10 years).

Treasury Inflation-protected Security (TIPS). A TIPS is a security whose par value increases with inflation and which yields some interest; the par value is adjusted, and

the interest is paid semi-annually. Because the par value of a TIPS increases with inflation, the principal is protected against loss due to inflation.

Treasury Note. A treasury note is a longer-term security (between one and 10 years) which pays interest semi-annually and is redeemed at maturity for the par value.

U.S.-Chartered Depository Institutions (player). This sector includes federal savings banks, commercial and savings banks which have received either federal or state authorization to engage in banking practices (a charter), cooperative banks, savings and loan associations, and international banking facilities. Assets and liabilities between institutions within the sector are not included (Board of Governors of the Federal Reserve System 2019).

Commercial Bank. A commercial bank offers deposit and loan services, as well as simple investment options for the public — that is, for individuals or businesses.

Cooperative Bank. A cooperative bank is owned by its customers. They offer services similar to a commercial bank but are generally small and localized. Because they are member-owned, the bank's profits are returned to its members (Surbhi 2017).

International Banking Facilities. An international banking facility (IBF) allows U.S.-chartered depository institutions to offer some banking services to foreign citizens and organizations. IBFs must be maintained separately from core banking operations.

Savings and Loan Association. A savings and loan association (SLA) offers many of the same services as a commercial bank, although it tends to be locally-oriented and focused on residential mortgages. Its ownership structure may be similar to that of a cooperative bank, or it may be owned by shareholders.

Savings Bank. A savings bank collects money from clients and invests that money in a conservatively (e.g., in Treasury securities) to provide interest to their clients. The money invested is called a savings deposit and cannot be withdrawn without some prior notice to the bank. This differs from a demand deposit, from which money can be withdrawn without notice (e.g., from a checking account) (The Editors of Encyclopaedia Britannica 2020).

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