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# THE INTERNATIONAL MONETARY SYSTEM AND INTERNATIONAL FINANCIAL SYSTEM AS AN ANALOGY TO THE COPERNICAN HELIOCENTRIC SYSTEM: A SIMPLE MULTI-LAYERS NETWORK MODEL WITH SIMULTANEOUS REGIME CHANGES

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Working Paper 31716
http://www.nber.org/papers/w31716

NATIONAL BUREAU OF ECONOMIC RESEARCH
1050 Massachusetts Avenue
Cambridge, MA 02138
September 2023

The authors thank Joshua Aizenman, Barry Eichengreen, Harold James, Olivier Jeanne, Robert McCauley, Antoine Parent and Marc Wiedenmier for comments on earlier versions. They also thank the participants in the World Copernican Congress of Kracow (Poland, May 24-26 2023) and the Leipzig Colloquium (online, December 14th 2023) for useful questions and remarks. The views expressed herein are those of the authors and do not necessarily reflect the views of the National Bureau of Economic Research.

The International Monetary System and International Financial System as an Analogy to the Copernican Heliocentric system: A simple multi-layers network model with simultaneous regime changes
Michael D. Bordo and Cécile Bastidon
NBER Working Paper No. 31716
September 2023
JEL No. C3,C82,E42,F33,G15,N2

**ABSTRACT**

The evolution of the IMS and IFS in the past several hundred years can be viewed through the lens of the Copernican heliocentric system developed over 500 years ago. We trace out the evolution across regimes of the IMS and IFS in terms of network representations of the Copernican system. We provide a simple, fully testable theoretical model whose assumptions are based on these representations. The IMS and IFS are described by a two-layer graph whose three key features (hub, core, distances) are affected by nonlinear joint regime changes linked to a technological, institutional, geopolitical and regulatory environment variable. We conclude with a discussion of some perspectives of the future of the international monetary and financial systems. Our analysis is based on economic history, theory and some resonant concepts from astrophysics.

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# Introduction

In this paper we argue that the evolution of the International Monetary System (IMS) and International Financial System (IFS) in the past several hundred years can be viewed through the lens of the Copernican heliocentric system developed over 500 years ago. Our contribution is twofold. On the one hand, we connect literatures in economic history and the theory of complex networks with some resonant concepts from astrophysics. Elaborating on the equivalence of single-hub tree networks diagrams and stellar systems, we trace out the evolution across regimes of the IMS/IFS in terms of network representations of the Copernican system. The specific network representations provided by the analogy allows us to propose a novel reading of monetary and financial history, shedding light on both long-term trends and future prospects. We also provide a simple, fully testable theoretical model whose assumptions are based on these representations. The IMS and IFS are described by a two-layer graph whose three key features (hub, core, distances) are affected by non-linear joint regime changes linked to a technological, institutional, geopolitical and regulatory environment variable. We conclude with a calibration of the theoretical model and a discussion of some perspectives for the future of the international monetary and financial systems.

There are five main foundations of the analogy. The first foundation, which is also the starting point of our reasoning, is that the Copernican system revolutionized the representation of the universe from a theoretical model that preceded observation. This point is not necessarily the best known: Copernicus is systematically associated with the discovery of the heliocentric system, but the essentially theoretical nature of his contribution is more rarely mentioned. Yet it helps explain why, unlike Galileo, the Church did not pursue Copernicus, as his work was widely regarded as a mathematical treatise. In fact, Copernicus' sine tables, essential to the study of any stellar system, whatever its center, remained the standard for centuries. As the science historian Owen Gingerich states, "in the first chapters, Copernicus gives his strongest arguments in favor of a model of the planetary system with the sun at its center - arguments based on simplicity, harmony and aesthetics, since it was impossible at that time, before the invention of the telescope, to find observational evidence of the Earth's motion." (Gingerich, 2004, p. 54). The same question of the tensions between theoretical modeling and observation arises in the case of the IMS/IFS. The forms of these systems evolve, and the ability to develop relevant theoretical models and at the same time define the appropriate measurements to provide an empirical validation is a true challenge, as illustrated for example by the rise of cryptocurrencies and digital currencies in general.

The second main foundation of the analogy is that the Copernican model was not only innovative, but also much simpler than the previous models, as illustrated by Figure 1 below. This aspect of Copernicus' work is not necessarily well known either. The Ptolemaic system (Figure 1 left), which preceded the Copernician system (Figure 1 right) as the reference representation of the movement of the Sun and planets, had undergone successive additions over time as observations became more precise, in order to remain compatible with these observations. In this context, "his successors admired Copernicus for a completely different aesthetic reason [than the heliocentric theory], namely the elimination of [epicycles]. (Gingerich, 2004, p. 63-64). In the augmented Ptolemaic system, the planets revolve around

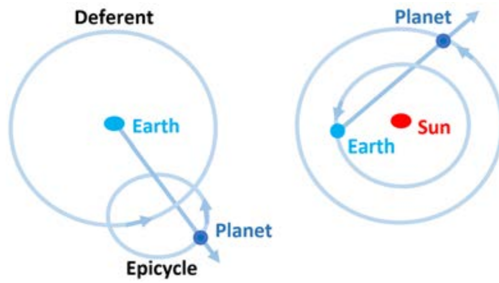


Figure 1: Augmented geocentric system of Ptolemy (left), heliocentric system of Copernicus (right)

the Earth - not directly on orbits, but on a small circle (epicycle) which itself rotates on a large circle (deferent). In comparison, the Copernican model is not only radically innovative, but also much simpler. Our analogy is inspired by this search for simplicity in modeling.

The third main foundation of the analogy is that the Copernican system paved the way for further developments in astrophysics, from the 16th century to the present: "Until a massive and precise observation protocol was developed by Tycho Brahe [in the last years of the 16th century], the necessary data was not available. Once available, it took less than fifteen years for Kepler to identify the elliptical compression of the orbits" (Gingerich, 2004, p. 181). This includes the discovery of the elliptical orbits by Kepler in the early 17th century, the existence of planetary satellites, the multiplicity of solar systems, etc. Our analogy between the international monetary and financial systems and stellar systems is essentially inspired by Copernicus' heliocentric model, but also by these later developments. A recent development, in particular, constitutes the fourth foundation of the analogy: modern astrophysics documents the life cycles of stars and their stellar systems. In other words, if the characteristics of the IMS and IFS are not time-invariant, neither are those of stellar systems, considering a relevant time horizon, which is that of astrophysics. This life cycle, marked by a succession of periods in which the stars and their solar systems display essentially homogeneous characteristics, is illustrated by Figure 2.

This cycle is generally considered to comprise four stages: "We identify four galaxy groups [...] that can be evolutionarily linked through a life cycle [...]. Galaxies first consume their gas mostly through [...] star formation (C1); then enter into a transition phase of intermediate gas richness (C2-C3) [...]; before settling into retirement as [...] systems with residual levels of [...] activity (C4)." (Yesuf and Ho, 2020). The monetary and financial systems are also characterized by successive relatively homogeneous periods. For the last century and a half, for the international monetary system, we distinguish between the Classical gold standard, the Gold exchange standard, Bretton Woods and the Managed float; and for the international financial system we distinguish between the pre-World War first era of globalization, disintegration during the interwar and Bretton Woods period and rejuvenation as the second era of globalization since.

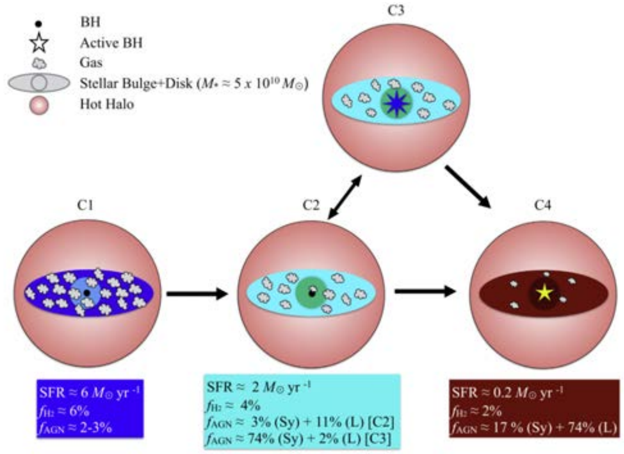


Figure 2: Schematic diagram of clusters of stars C1 to C4 over lifecycles (source: Yesuf and Ho, 2020

The fifth and last main foundation of the analogy is that the network representations used today for the study of the IMS/IFS can be directly transposed into the language of stellar systems, as illustrated by the examples of Figure 3(left) which represent networks of currency quotes, and Figure 3(right) representing networks of stock markets prices. Stellar systems are composed of stars, planets orbiting the stars, and satellites orbiting the planets. Distances are measured by the radii of the orbits. Monetary and financial networks are composed of hubs, secondary hubs, and weakly connected nodes. Distances are measured by the lengths of the edges. These three common characteristics of stellar systems, on the one hand, and monetary and financial systems, on the other hand, directly support the analogy-inspired modeling that we propose in what follows.

Based on these five foundations of the analogy, the rest of the paper is organized as follows. Section 1 presents the methods of the analogy. Section 2 details the historical evolution of the IMS/IFS and provides a summary of the main concerns relating to current developments in IMS/IFS from the perspective of this original network modeling. Section 3 proposes a testable theoretical model that synthesizes the whole range of literatures on which the analogy relies, and Section 4 offers a calibration exercise for this model. We conclude by formulating some main lessons and discussing limitations of the modeling strategy.

# 1 The Methods of the analogy

## 1.1 Modeling monetary and financial systems as stellar systems

In what follows, we detail the analogy to the Copernican heliocentric system as support for our description of the history of the IMS and IFS in section 2, and the theoretical modeling in sections 3 and 4. We do this in three steps: the equivalence of tree network diagrams and star system diagrams; the parallel between star life cycles and tree network regime shifts;

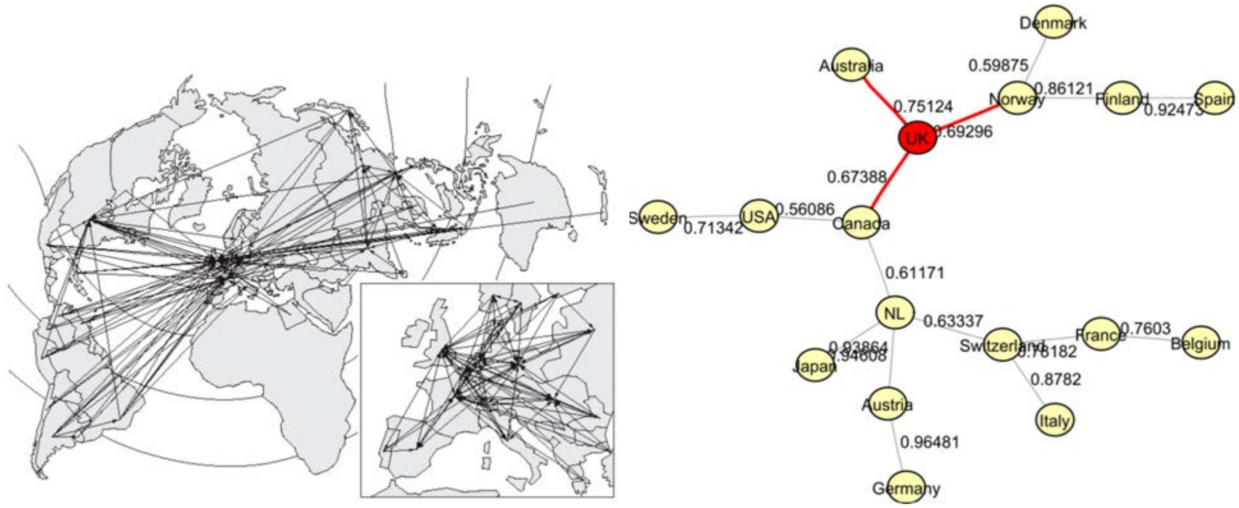


Figure 3: Network of currencies quotes, 1900 (left, source: Flandreau and Jobst, 2005), Network of stock markets prices, Interwar (right, source: Bastidon et al. (2023))

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and the causal variables of regime shifts.

At a general level, on the one hand, over the past century and a half, the structure of monetary and financial systems has been essentially stable within major eras, but very different from one era to another. This specific fact leads us to use a regime-switching network model in which key network characteristics are stable within eras but can vary from era to era. It is discussed in detail in subsection 1.2. On the other hand, in terms of networks, a stellar system corresponds to a specific network model, i.e. a tree network. This fact is discussed in detail in the current subsection. The three stages of Figure 4 describe the equivalence between a tree network diagram characterized by the three key characteristics of hub(s), core (nodes located in the close neighborhood of the main hub), and distances between the nodes (Figure 4 left) and a Copernicus-type stellar system diagram (Figure 4 right).

As documented in the existing literatures in Financial macroeconomics and Statistical mechanics, tree networks also describe in a relevant way monetary and financial systems (see notably, for minimal spanning trees, Bastidon and Parent, 2022; or Bastidon et al., 2020). This observation of the relevance, documented in their respective reference literatures, of the same network model for the representation of stellar systems and monetary and financial systems leads us to take, as a starting point for the modeling of monetary and financial systems, tree network models whose structures are equivalent to those of star systems (Figure 4). In sections 1 and 2, we systematically provide both diagrams: the network diagram for comparability with the existing literature, and the star system diagram for readability and as a support for the discussion based on the analogy.

In the IMS representation, the three key features of the stellar system / network (Figure 5 left) are then the hub, corresponding to the main underlying asset of confidence (nomi-

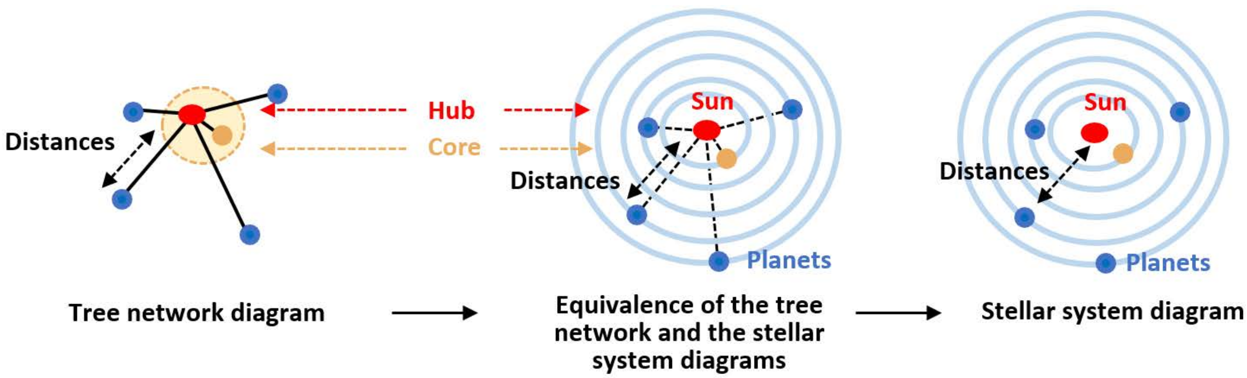


Figure 4: From tree network diagrams (left) to stellar system diagrams (right). Schematic representation of the equivalence (middle) of the structure of a weighted tree network with one hub, and a stellar system.

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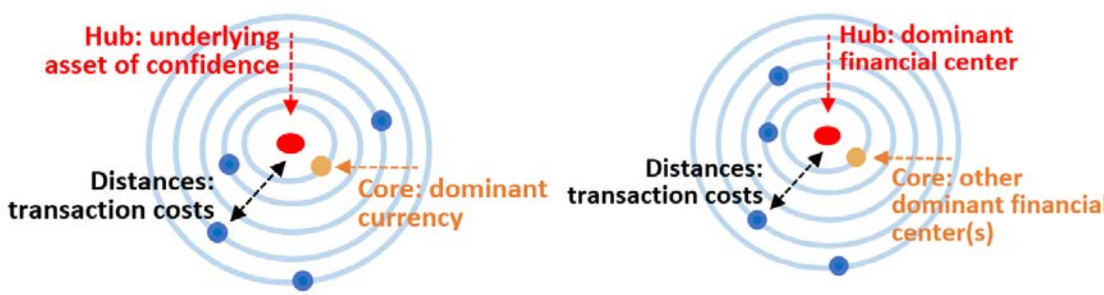


Figure 5: Key features of the stellar system diagram of the IMS (left) and IFS (right).

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nal anchor), whether tangible (gold) or intangible (monetary policy credibility, Willems and Zettelmeyer, 2022); the core, corresponding to the dominant currency(ies), and distances corresponding to transaction costs in foreign exchange operations, low for permanently fixed exchange rates and high otherwise. For the IFS representations, the three key features (Figure 5 right) are the hub, corresponding to the dominant financial center; the core, corresponding to other dominant financial center(s); and distances, corresponding to transaction costs in international capital flows, low for low regulation and high for high regulation.

## 1.2 The IMS and IFS as a 2-layer multivariate regime switching graph model

To model the joint long-term dynamics of the monetary and financial systems, the network representation of the IMS and the IFS are included in a simple 2-layer regime-switching network model summarized by Figure 6. The first layer corresponds to the IMS (Figure 6 left) and the second layer to the IFS (Figure 6 right), both described by the previously presented three key variables of networks structures i.e. their hub (upper panels), core (middle panels) and distances (bottom panels). For each layer, each variable has two or three possible states, i.e. for the hub of the IMS, gold standard / no gold standard (upper right); or for the hub of the IFS, London / New-York (upper left), over four eras: the Classical gold standard in the 1st era of globalization, the Gold exchange standard in the Interwar, the Bretton Woods era, and the managed float in the 2nd era of globalization.

Figure 7 provides, for the IMS and IFS layers (in columns) and for each eras (in rows), the two equivalent tree network and stellar system diagrams. These representations are discussed in detail by era in Section 2 and form the basis of the theoretical model developed in sections 3 and 4. As a preliminary, in the following we introduce the causal variables of the system regime switchings.

## 1.3 Why do the IMS/IFS regimes switch?

The stages of the life cycle of stars are well documented. The transition from one type of star to another depends on the nature of the reactions that take place (e.g., Yesuf and Ho, 2020). By contrast, the causes of the emergence of specific network structures, corresponding to IMS/IFS regime switchings, are less widely studied, to the point where they would even remain "terra incognita" in the literature (Flandreau and Jobst, 2005). Recent theoretical models focus on the configurations and crises of (in particular) monetary regimes, rather than regime switchings. In particular, Farhi and Maggiori (2018) provide an IMS model based on reserve asset issuance and demand in different configurations of currency dominance and exchange rate regimes; and Fernández-Villaverde and Sanches, 2023 a growth and inflation model of a small open economy under a gold standard regime.

However, "even anchors of stability such as world providers of reserve currencies do end up sharply devaluating under bad enough circumstances" (Farhi and Maggiori, 2018). The model we propose focuses on describing these circumstances and the system states before and

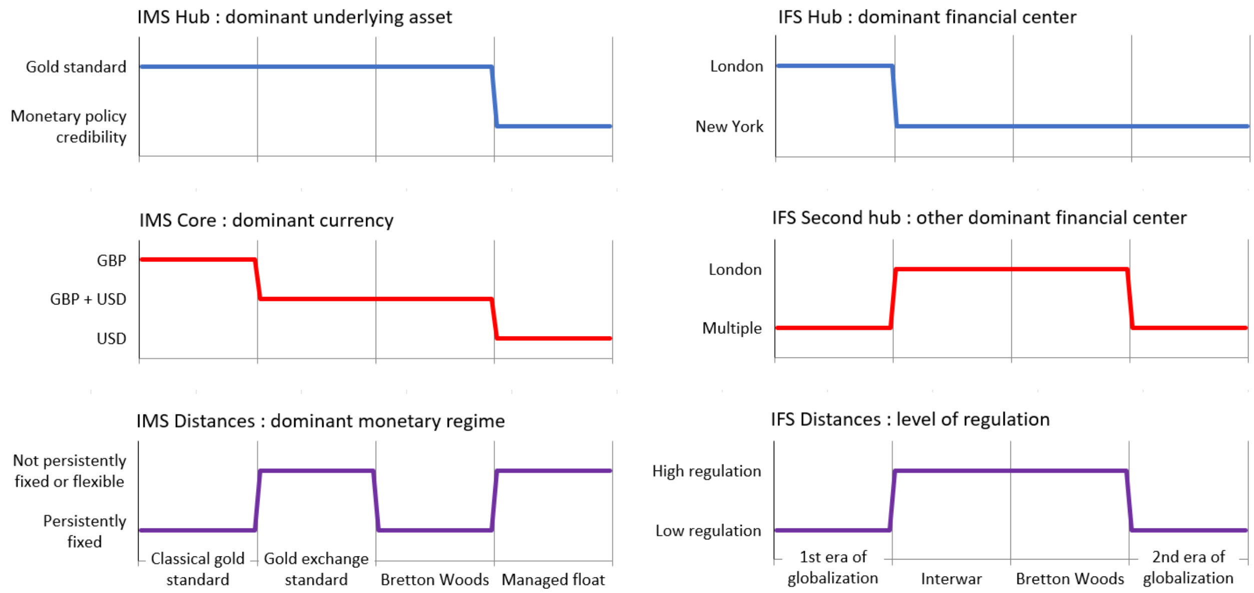


Figure 6: Switching regime network model, IMS layer (left) and IFS layer (right): overall dynamic representation.

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after their occurrence. Based on different types of literatures, we identify four factors which may explain regime switches. These are: changes in technology, changes in institutions; geopolitical forces (including major conflicts); and changes in governance (e.g., regulation). In the theoretical model proposed in section 3, we refer to these causes as "components" of the environment variable, which is composed of four distinct vectors of time-series.

In detail, the technological component refers to the global advances and convergence in technology and growth dynamics. For example, Sylla (2002) highlights the crucial nature of the prior financial revolutions in the three economies that were pioneering in creating durable monetary and financial institutions (the Netherlands, the UK, then the USA). He argues that financial revolutions and, more generally, the dynamics of financial development came before the industrial revolutions (especially in the cases of the UK and US) that gave these countries economic and financial dominance in the past four centuries.

The institutional component refers to major institutional changes in the organization of monetary and financial systems. An example with particularly noteworthy consequences was the foundation in 1913 of the modern Federal Reserve System, which led to the consolidation of U.S. banking and financial institutions and markets. This dramatic institutional innovation allowed the US monetary and financial system to catch up to its clear dominance in global economic performance achieved by 1900. This set the stage for the later dominance of the U.S. dollar.

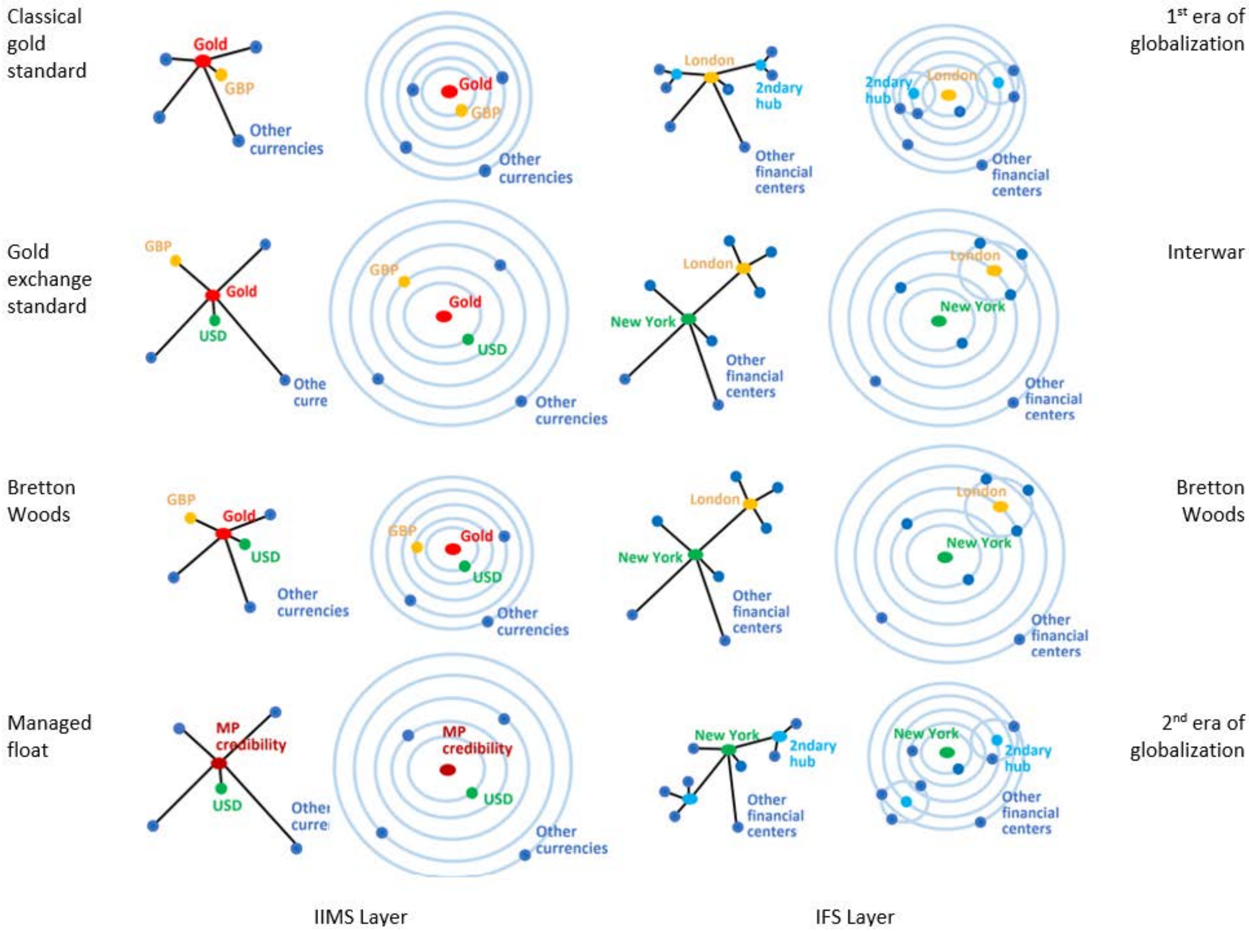


Figure 7: Switching regime network model, IMS layer and IFS layer: network and stellar systems diagrams.

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The geopolitical component refers first to major conflicts and the associated demographic and economic costs, especially World Wars I and II. (see, in particular, Kindleberger, 1973 on the "formation of financial centers"). It also refers to other geopolitical factors e. g., alliances and the end of colonial empires. From this perspective in particular, Cassis (2010); or Eichengreen et al. (2018) point out that the persistence of, respectively, international financial centers and international monetary systems, associated with the liquidity of local financial markets, the availability of trade finance, and the interest rates on newly-issued debt, would be overestimated.

Finally, the governance component refers both to the role of international organizations like the councils of foreign bond holders before WWI, and subsequently the IMF, G10, G20, and the BIS in enforcing and amending the operating rules of the game of the IMS and IFS. It also refers to major reform proposals and their implementation. This was notable in the era of the Classical Gold standard in proposals by e.g. Ricardo, Jevons, Marshall, Fisher, Wicksell and Keynes (Bordo, 1984), some of which were partially implemented after World War I at the Genoa conference (1922). During the era of the Gold exchange standard, a key proposal for reform by Ragnar Nurske (Nurkse, 1944) and then by Keynes (1941) and White (1943), the adjustable peg, was later adopted in the Bretton Woods Agreement of 1944. The alternative case for floating exchange rates made by Gottfried Haberler was rejected (Bordo et al., 2002). In the case of the Bretton Woods regime, proposals for reform to create a global central bank by Triffin (1960) and others were not adopted but the case for floating by Milton Friedman (Friedman et al., 1953) was ultimately implemented with the collapse of the Bretton Woods system in 1973

These components of the environment variable form both the threshold variables and the explanatory variables for the joint changes in the three characteristics of the IMS layer and the IFS layer of networks in our proposed model.

# 2 Historical evolution of the IMS and IFS

## 2.1 Classical Gold standard

In this section, we propose an original reading of the historical evolution of the IMS and IFS, relying on the analogy. For each era, this reading is based on the equivalents tree network and stellar system diagrams, summarized in Figure 7.

Figure 8 presents the Classical Gold standard. The model at a glance highlights the central place of Sterling as the IMS core, based on Gold as the IMS hub, and the financial center in London as the IFS hub. It also emphasizes low transaction costs in both foreign currency transactions and international capital flows (IMS and IFS short distances), i.e the absence of capital controls and major advances in communications after the laying of the first transatlantic cable (Kavesh et al., 1978).

In detail, the representation of the IMS layer provides a relevant description of the role of Gold (IMS hub) as money, with special properties as store of value, means of exchange, and

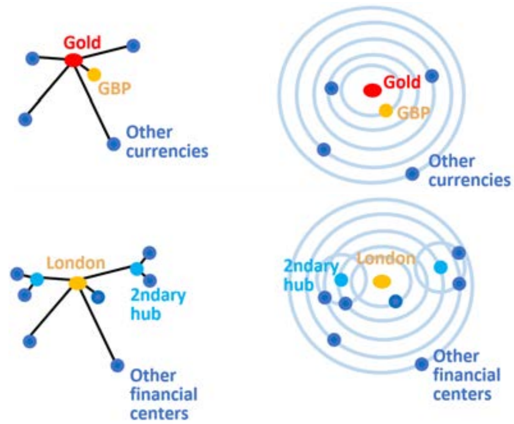


Figure 8: Tree network (left) and stellar system diagrams (right), Classical Gold standard. International monetary system (upper), International financial system (lower).

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unit of account. In this context the pound sterling (IMS core) convertible into gold evolved as the key currency because of network externalities for trade such as invoicing, the standard of value property being based on safe assets, political stability etc. The representation of the IFS layer encompasses the development in the nineteenth century of London as the IFS hub, as the principal securities and commodities markets, as well with the other European financial centers in the IFS core. The networks that developed were based on path dependency. This followed a path dependent process based on Sterling bills as the key financial instrument (Coppola et al., 2023). Note that the correspondence between dominant currency and dominant financial center, observed for each of the eras described in this section, constitutes one of the stylized facts underpinning the theoretical modeling assumptions in Section 3 and 4.

## 2.2 Gold exchange standard

Figure 9 presents the model for the gold exchange standard era. It mainly highlights the decline in the central place of Sterling, in the IMS core, as the dominant international currency in favor of the dollar beginning in the 1920s. In the IFS, the financial center in London, as the hub of the IFS, gradually has been replaced by New York. The era is characterized by both high transaction costs in foreign currency transactions and international capital flows, seen in long distances in both the IMS and IFS, reflecting the closing of financial markets during World War I and the advent of exchange and capital controls.

The main stylized facts of the period, captured by the model, are as follows. In the IMS layer, Gold remained the hub, but the core is now composed of Sterling and Dollars. The position of both depends on their track record in maintaining convertibility into gold (Eichengreen and Flandreau, 2009). Sterling devolves with the U.K.'s loss of economic power. This corresponds to the geopolitical component of the transition environment variable. The IFS layer displays weak networks (long distances) centered on New York as the IFS hub;

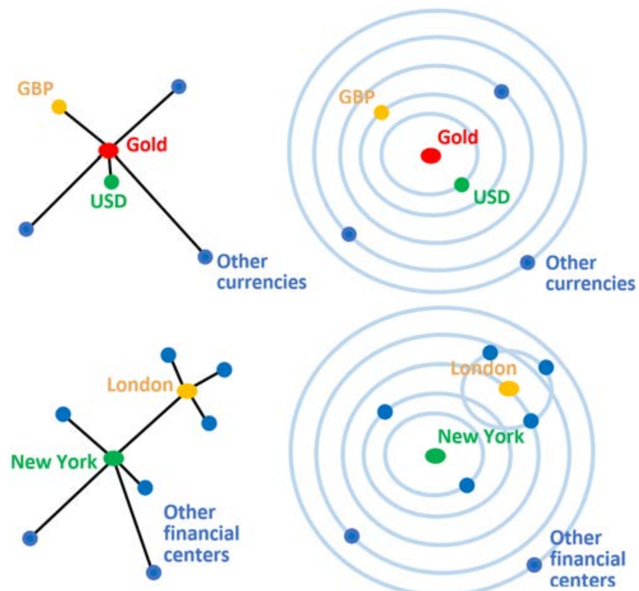


Figure 9: Tree network (left) and stellar system diagrams (right), Gold exchange standard. International monetary system (upper), International financial system (lower).

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and London as the IFS core, as New York takes over in the sovereign debt and money markets. This corresponds to the technological and institutional components of the environment variable.

## 2.3 Bretton Woods

Figure 10 presents the Bretton Woods era. The model mainly emphasizes the central place of the US dollar in the IMS core, based on gold as the IMS hub, and the rise to dominance of New York as the premier financial center i.e IFS hub. The era is characterized by low transaction costs in foreign currency transactions because exchange rates were fixed, seen as IMS short distances; but high transactions costs in international capital flows with widespread capital controls, seen as IFS long distances. This illustrates for the first time the possibility of a discordance in the density of the IMS and IFS layers.

The main stylized facts captured by the model are as follows. In the IMS layer, gold (the IMS hub) and the dollar (in the IMS core) standard become dominant, although the Bretton Woods agreements were initially based on two key currencies, the dollar and the pound sterling, Sterling being viewed as first line of defense for the dollar (Bordo et al., 2019). Sterling's position as a dominant currency ended after the 1967 devaluation and the crippling of the sterling area (Schenk, 1998). In this context, the discordance between low IMS distances and high IFS distances shows the dollar being used for trade, but with little capital flows because of capital controls. The position of the US as a financial intermediary (Despres et al., 1966) in the context of the widely believed at the time Triffin dilemma (Triffin,

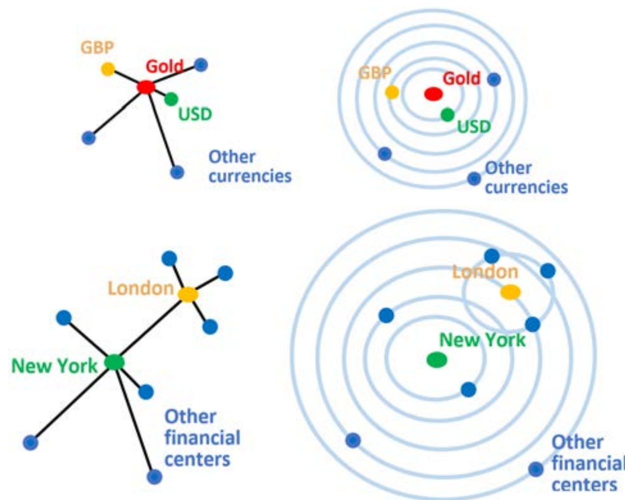


Figure 10: Tree network model (left) and stellar system diagrams (right), Bretton Woods. International monetary system (upper), International financial system (lower).

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1960), weakened the Gold/Dollar standard. This was the case especially after the 1965 US fiscal/monetary shocks of President Lyndon Baines Johnson's Great Society program and the Vietnam war. As the dollar came under increased attack capital controls lost their bite in the face of financial innovation, eg. in futures markets and trade invoicing (Marston, 1997). These developments illustrate the interactions between the regulatory component of the environment variable and its other components. At the same time, in the IFS layer New York cemented its position as key financial center (the IFS hub), with London in the IFS core still important as the reference financial center for the Sterling area along with the emergence of the Eurodollar market in London Schenk (1998); Naef (2022).

## 2.4 Managed Float

Figure 11 describes the Managed Float period. The model mainly highlights the central place of the US dollar in the IMS core and the financial center of New York as the IFS hub. This is in the context of the disappearance of an official link to gold in the IMS hub after the passage of the Second Amendment to the IMF Articles of Agreement in 1976. It also emphasizes the rise of plural regional financial centers (eg. in Tokyo, Hong Kong, Frankfurt, Paris) with none being dominant in the IMS core. Once again, a discordance is observed between relatively high transaction costs in foreign currency transactions, related to currency risk and low interoperability of banking systems i.e., IMS long distances; and low transactions costs in deregulated international capital flows i.e. IFS short distances. The IMS layer illustrates that despite floating which creates domestic money sovereignty, the US Dollar (the IMS core) survives as the dominant currency for trade and financial flows, as documented in an extensive literature (e.g., Ilzetzki et al., 2022, 2019; Ito and McCauley, 2019). The IFS layer illustrates new regional networks with focal points in New York (IFS hub) and Europe (EMS/EMU, IFS core).

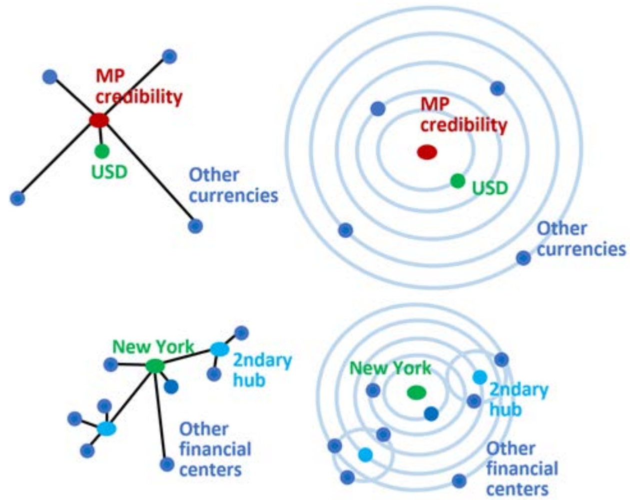


Figure 11: Tree network model (left) and stellar system diagrams (right), Managed float. International monetary system (upper), International financial system (lower).

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Generally speaking, this presentation of the historical development of IMS/IFS serves a dual purpose. On the one hand, it allows us to verify that the structure of the two-layer tree network model, with regime switchings related to an environmental variable, does indeed provide a relevant description of the joint evolutions of the two systems. Secondly, it enables us to propose a succinct presentation that is simple and structured by a guiding thread which is appropriate to a comparative historical approach to a century and a half of monetary and financial history that is particularly dense in structural shocks. Both points allow us, as a conclusion of section 2, to propose a prospective analysis based on the modeling hypotheses previously retained; and, in section 3, to propose a theoretical model associated with these hypotheses.

## 2.5 The Future

The model at a glance described in Figure 12, corresponding to the assumptions of the two-layer regime-switching network model, could have the following characteristics. On the one hand, the persistence of the central place of the US dollar in the IMS core and the financial center in New York as the IFS hub, coexisting with rising regional currencies in the IMS core and financial centers in the IFS core. On the other hand, transaction costs in foreign exchange trades remaining relatively high, related to currency risk, creating IMS long distances, but possibly decreasing; and low (and decreasing) transactions costs in international capital flows seen as IFS short distances, but possibly decreasing.

As regards the IMS layer, the most widely debated question in the literature today is that of the US dollar versus the Chinese Renminbi. In the absence of a major environmental shock (in the sense of the technological, institutional, geopolitical and governance variables),

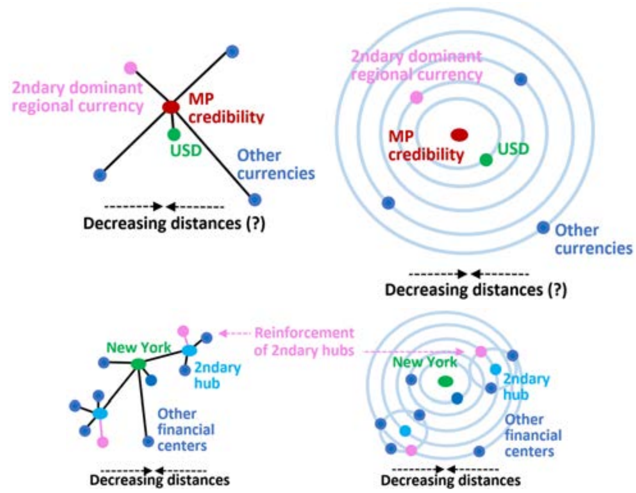


Figure 12: Tree network model (left) and stellar system diagrams (right), prospective future developments. International monetary system (upper), International financial system (lower).

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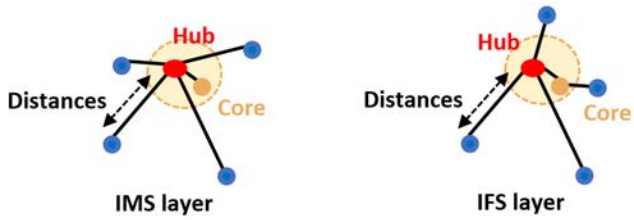
dollar dominance in the IMS core is likely to be assured Ilzetzki et al. (2022, 2019); Ito and McCauley (2019). This does not rule out a place for regional currencies, notably the Euro in the IMS core, with a truly multipolar system remaining unlikely (Eichengreen et al., 2022). As regards IMS distances, digital currency(ies) likely based on the dollar could reduce transaction costs in currencies by improving interoperability (Brunnermeier et al., 2019). In this context, the IMS layer would be characterized by growing regional networks in the IFS core but New York would still dominate as the IFS hub. Finally financial innovation, e.g. digitalization, would lead to new network patterns with decreasing transaction costs (i.e decreasing IFS distances).

# 3 A simple multiplex model with simultaneous IMS and IFS regime changes

## 3.1 Environment variable and transition variable of the regime-switching model

In this section we provide a formal description of the model, consisting of a dynamic two-layers multiplex (*i.e.* a multi-layer network): the first layer corresponds to the international monetary system, the second layer to the international financial system. Both the multiplex structure and assumptions about the structure of these layers are based on the reference literature in economic history and complex systems reviewed in Sections 2 and 3. Our contribution is twofold. On the one hand, we propose a simple model of the international monetary and financial systems, using and combining the original methods of multiplex graphs and non-linear regime-switching models. In addition, all the hypotheses of our model are

(a)

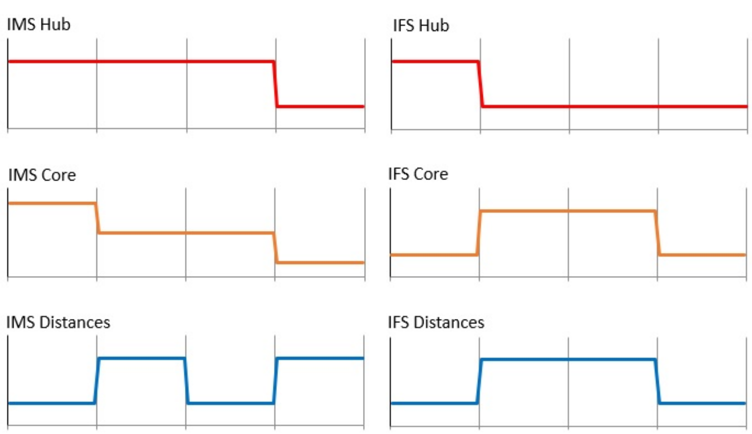



$$j = 0, \dots, n$$

$$\textbf{(b)}\ \mathscr{D}_{M,t} = \underset{i=0,\dots,n}{} \begin{pmatrix} 0 & \gamma_{Mt} d_{M\ 0,1\ t} & \gamma_{Mt} d_{M\ 0,2\ t} & & & \dots & \gamma_{Mt} d_{M\ 0,n\ t} \\ \gamma_{Mt} d_{M\ 1,0\ t} & 0 & 0 & & & \dots & 0 \\ \gamma_{Mt} d_{M\ 2,0\ t} & 0 & 0 & & & & \\ & & & 0 & & & \\ & & & & 0 & \dots & \dots \\ \dots & \dots & & & \dots & 0 & 0 \\ \gamma_{Mt} d_{M\ n,0\ t} & 0 & & & \dots & 0 & 0 \end{pmatrix}$$

$$j = 1, \dots, n$$

$$\mathscr{D}_{F,t} = \underset{i=1,\dots,n}{} \begin{pmatrix} 0 & 0 & \dots & 0 & \gamma_{Ft} d_{F\ 1,k\ t} & 0 \\ 0 & 0 & \dots & & 0 & \gamma_{Ft} d_{F\ 2,k_1\ t} \\ \dots & \dots & 0 & 0 & \dots & \\ 0 & & 0 & 0 & & \dots \\ \gamma_{Ft} d_{F\ k,1\ t} & 0 & \dots & & 0 & \gamma_{Ft} d_{F\ k,k_1\ t} \\ 0 & \gamma_{Ft} d_{F\ k_1,2\ t} & & \dots & \gamma_{Ft} d_{F\ k_1,k\ t} & 0 \end{pmatrix}$$




(c)

$$\textbf{(d)}\ S_t = \begin{bmatrix} T_t \\ I_t \\ W_t \\ R_t \end{bmatrix} \longrightarrow \begin{cases} \gamma_{Mt}\ .\ A_M\ .\ \mathscr{D}_{M,t} = D_{M,t} & \text{(IMS layer)} \\ \gamma_{Ft}\ .\ A_{F,t}\ .\ \mathscr{D}_{F,t} = D_{F,t} & \text{(IFS layer)} \end{cases}$$

The two multiplex layers (IMS) and (IFS) consist of a hub, a core and other nodes connected to the hub and core by varying distances **(a)**. Their structure is described by the symmetrical matrices $\mathscr{D}_{M,t}$ and $\mathscr{D}_{F,t}$ where non-zero values correspond to the edges of the hub (in red) and core (in orange). The global distance component is shown in blue **(b)**. These variables are piecewise constant, with simultaneous jumps **(c)** determined by an environment variable $S_t$ with four components: technological, institutional, geopolitical and regulatory **(d)**.

Figure 13: Summary representation of the model

directly testable, in particular the structure of graphs, their dynamic properties of stable regimes with simultaneous jumps, and the causal effect of the technological, institutional, geopolitical and regulatory environment on regime changes and graph structure in the different regimes. In Section 4, we propose a calibration exercise of this general theoretical form.

Each layer consists of a star network. The nodes correspond to currencies, in the international monetary system layer; and to financial centers, in the financial system layer. As described above, the network has three distinctive characteristics: the node that occupies the hub position of the layers ("hub"), the nodes that are located at the heart of the network at a short distance from the hub (IMS layer "core") or as secondary hubs (IFS layer "core"), and the more or less dense or extensive nature of the network as a whole ("distances"). These three characteristics are a function of a four-variate environment variable describing the technological, institutional, geopolitical and regulatory environment, according to a non-linear relationship characterized by stable regimes. The geopolitical and regulatory environment vectors form the transition variables. In the event of an extreme geopolitical or regulatory event, the associated threshold is exceeded, and the hub, core and distance characteristics of each layer are affected by a simultaneous regime switching. The value of each of these characteristics after the shock depends on the four vectors of the technological, institutional, geopolitical and regulatory environment forming the environment variable. In the general case, and in the absence of extreme event, neither threshold is crossed and there is no regime switching. This overall structure is summarized in Figure 13.

The environment variable is denoted $S_{it}$ where $i$ corresponds to countries and $t$ to time. It is composed of the four main environmental characteristics of international monetary and financial systems: technology ($T_{it}$), institutions ($I_{it}$), geopolitics and conflicts ($W_{it}$), and regulation ($R_{it}$), as follows:

$$S_{it} = \begin{bmatrix} T_{it} \\ I_{it} \\ W_{it} \\ R_{it} \end{bmatrix} \tag{1}$$

## 3.2 International Monetary System

The three characteristics of the IMS layer (see, for a summary, Figure 13 in the current Section; and for a complete representation, Figures 6 and Figure 7 in Section 1) are described by three specific matrices: the adjacency matrix $A_M$ describes the position of the edges and thus designates the hub, the hierarchical distance matrix $\mathscr{D}_{\mathrm{M}}$ describes the hierarchy of distances from each node to the hub and thus characterizes the core, and the final distance matrix $D_M$ describes the length of the edges and thus characterizes the extension of the network. All three matrices are square matrices of dimension $(n+1) \times (n+1)$. Index $i = 0$ corresponds to the dominant underlying asset $C_0$ of confidence in the system currencies, and indices $i = 1, ..., n$ correspond to currencies $C_1, ..., C_n$.

### 3.2.1 Adjacency matrix

The structure of the adjacency matrix $A_M$ is as follows :

$$A_M = \underset{i=0,...,n}{} \overset{j=0,...,n}{\begin{pmatrix} 0 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 0 & 0 & & & ... & 0 \\ 1 & 0 & 0 & & & & \\ 1 & & & 0 & & & \\ 1 & & & & 0 & ... & ... \\ 1 & ... & & & ... & 0 & 0 \\ 1 & 0 & & & ... & 0 & 0 \end{pmatrix}} \tag{2}$$

That is:

$$\begin{gathered} a_{M\ i,j} = 1 \text{ if } i = 0 \text{ or } j = 0,\ (i,j) \neq (0,0) \\ a_{M\ 0,0} = 0 \\ a_{M\ i,j} = 0\ \forall\ i \neq 0 \text{ or } j \neq 0 \end{gathered} \tag{3}$$

As the network is undirected, the matrix is symmetrical, like the other two matrices describing the IMS structure.

Based on the literature discussed above, we hypothesize that asset $C_{M\ 0,t}$ that underlies confidence in the currencies of the international monetary system is unique in each time $t$. $A_M$ is therefore unchanged over time: each of the currencies is uniquely linked to this specific asset. When a regime switching occurs, this asset is likely to change, as follows:

$$\begin{gathered} C_{M\ 0,t} = f_M\left(T_t, I_t, W_t, R_t\right) \\ C_{M\ 0,t} = \{G, MP, OT\} \end{gathered} \tag{4}$$

$C_{M\ 0,t}$ takes three possible values over the period of study: gold ($G$), monetary policy credibility ($MP$). In order to propose as general a specification as possible, we include a third possible value for $C_{M\ 0,t}$, corresponding to neither of the two values observed so far, that is "other" ($OT$). The use of a different dataset for the study of earlier or prospective systems does not change the structure of the adjacency matrix insofar as the asset which underlies confidence is always unique and indexed 0. The non-linear form of function $f_M\left(T_t, I_t, W_t, R_t\right)$ describing the evolution of $C_{M\ 0,t}$ in relation to the geopolitical $W_t$ and regulatory $R_t$ components of the environment variable is described in more detail below.

### 3.2.2 Hierarchical distance matrix

The hierarchical distance matrix $\mathscr{D}_{\mathrm{M,t}}$ establishes the hierarchy of distances corresponding to the edges of the adjacency matrix. Its structure is as follows:

$$\mathscr{D}_{M,t} = \underset{i=0,\dots,n}{} \overset{j=0,\dots,n}{\begin{pmatrix} 0 & d_{M\ 0,1\ t} & d_{M\ 0,2\ t} & & & \dots & d_{M\ 0,n\ t} \\ d_{M\ 1,0\ t} & 0 & 0 & & & \dots & 0 \\ d_{M\ 2,0\ t} & 0 & 0 & & & & \\ & & & 0 & & & \\ & & & & 0 & \dots & \dots \\ \dots & \dots & & & \dots & 0 & 0 \\ d_{M\ n,0\ t} & 0 & & & \dots & 0 & 0 \end{pmatrix}} \tag{5}$$

$\mathscr{D}_{\mathrm{M,t}}$ describes the structure of the core at time $t$, as follows:

$$\begin{gathered} d_{M\ i,0\ t} = d_{M\ 1,0\ t} \\ d_{M\ i,0\ t} = g_M\left(T_t, I_t, W_t, R_t\right) \\ d_{M\ i,0\ t} = \left\{\underline{d}_M, \overline{d}_M\right\},\ \forall i \neq 0 \\ \underline{d}_M \in \left[\underline{d}_{Ml}, \underline{d}_{Mu}\right] \\ \overline{d}_M \in \left[\overline{d}_{Ml}, \overline{d}_{Mu}\right] \end{gathered} \tag{6}$$

$$\text{with } 0 < \underline{d}_{Ml} < \underline{d}_{Mu} < 1 < \overline{d}_{Ml} < \overline{d}_{Mu}$$

$\forall i \neq 0$, the distance to the hub $d_{M\ i,0\ t} = d_{M\ 0,i\ t}$ is established in two possible intervals. $\underline{d}_M$ characterizes distances within the interval $[\underline{d}_{Ml}, \underline{d}_{Mu}]$. Currencies characterized by these short distances make up the core, i.e. are dominant in the functioning of the IMS. During the period under study, there are at most two at a time: the Pound sterling and the US dollar, during the Interwar and Bretton-Woods periods. In general, the dominant currency is unique. $\overline{d}_M$ characterizes long distances, within the the interval $\left[\overline{d}_{Ml}, \overline{d}_{Mu}\right]$. Currencies characterized by these long distances are outside the core, i.e. not dominant. These are all other currencies. When a switching regime occurs, the hierarchical structure of distances, and therefore the dominant currency, is likely to change. In the absence of regime change, the hierarchical distance matrix remains unchanged from one period to the next.

### 3.2.3 Final distance matrix

The final distance matrix $\mathrm{D}_{\mathrm{M,t}}$ describes the edges length, or network extension, in the IMS layer. This extension depends on the hierarchy established in the hierarchical distance matrix $\mathscr{D}_{\mathrm{M,t}}$, and on a global distance coefficient $\gamma_t$ taking high values when transaction costs are high and low values when transaction costs are low, i.e. the following structure:

$$\mathrm{D}_{\mathrm{M,t}} = \gamma_{Mt}\mathscr{D}_{\mathrm{M,t}} \tag{7}$$

$$
\mathrm{D}_{M,t} = \underset{i=0,\ldots,n}{} \overset{j=0,...,n}{\begin{pmatrix} 0 & \gamma_{Mt} d_{M\;0,1\;t} & \gamma_{Mt} d_{M\;0,2\;t} & & & \cdots & \gamma_{Mt} d_{M\;0,n\;t} \\ \gamma_{Mt} d_{M\;1,0\;t} & 0 & 0 & & & \cdots & 0 \\ \gamma_{Mt} d_{M\;2,0\;t} & 0 & 0 & & & & \\ & & & 0 & & & \\ & & & & 0 & ... & ... \\ ... & ... & & & ... & 0 & 0 \\ \gamma_{Mt} d_{M\;n,0\;t} & 0 & & & ... & 0 & 0 \end{pmatrix}} \tag{8}
$$

$$
\begin{gathered}
\gamma_{Mt} = h_M \left( T_t, I_t, W_t, R_t \right) \\
\gamma_{Mt} = \left\{ \underline{\gamma}_{Mt}, \overline{\gamma}_{Mt} \right\} \\
\underline{\gamma}_{Mt} \in \left[ \underline{\gamma}_{Ml}, \underline{\gamma}_{Mu} \right] \\
\overline{\gamma}_{Mt} \in \left[ \overline{\gamma}_{Ml}, \overline{\gamma}_{Mu} \right] \\
\underline{\gamma}_{Ml} < \underline{\gamma}_{Mu} < \overline{\gamma}_{Ml} < \overline{\gamma}_{Mu}
\end{gathered} \tag{9}
$$

The $\gamma_{Mt}$ coefficient is set in two possible value ranges. $\underline{\gamma}_{Mt}$ corresponds to a low value, within the range $\left[\underline{\gamma}_{Ml}, \underline{\gamma}_{Mu}\right]$. This interval corresponds to relatively low transaction costs under persistently fixed exchange rate regimes, i.e. short distances and a dense network. $\overline{\gamma}_{Mt}$ corresponds to a relatively high value, within the interval $[\overline{\gamma}_{Ml}, \overline{\gamma}_{Mu}]$. This interval corresponds to high transaction costs under flexible or non-persistently fixed exchange rate regimes, i.e. long distances and an extended network. When a regime switching occurs, the $\gamma_{Mt}$ coefficient and the hierarchical structure of distances are likely to change at the same time. In the absence of regime switching, the coefficient $\gamma_{Mt}$ and the hierarchical structure are unchanged from one period to the next.

### 3.2.4 Regime switching

IMS layer regime switchings are therefore described as follows:

$$\text{if } \begin{cases} W_t - W_{t-1} \geq W* \\ \text{or } R_t - R_{t-1} \geq R* \end{cases} \Rightarrow \begin{cases} C_{M\ 0,t} = f_M(S_t) = f_M \begin{pmatrix} T_{it} \\ I_{it} \\ W_{it} \\ R_{it} \end{pmatrix} \\ d_{M\ i,0\ t} = d_{M\ 0,i\ t} = g_M\left(S_t\right) = g_M \begin{pmatrix} T_{it} \\ I_{it} \\ W_{it} \\ R_{it} \end{pmatrix}, \ \forall i = 1, ..., n \\ \gamma_{Mt} = h_M\left(S_t\right) = h_M \begin{pmatrix} T_{it} \\ I_{it} \\ W_{it} \\ R_{it} \end{pmatrix} \end{cases}$$

$$\text{if } \begin{cases} W_t - W_{t-1} < W* \\ \text{and } R_t - R_{t-1} < R* \end{cases} \Rightarrow \begin{cases} C_{0,t} = C_{0,t-1} \\ d_{M\ i,0\ t} = d_{M\ 0,i\ t-1}, \ \forall i = 1, ..., n \\ \gamma_{M\ t} = \gamma_{M\ t-1} \end{cases} \tag{10}$$

In other words, crossing the extreme event variation threshold $W*$ for the geopolitical component $W_t$ of the environment variable (respectively, the variation threshold $R*$ for the regulatory component $R_t$) conditions a regime switching. When it occurs, we observe a simultaneous jump in the nature of the asset making up the hub $C_{0,t}$, i.e. the reference asset; in the hierarchy of distances $d_{M\ i,0\ t} = d_{M\ 0,i\ t}$ specifying the core, i.e. the dominant currencies; and in the $\gamma_{Mt}$ coefficient of global distances, i.e. the global level of transaction costs. For each of these variables, the value taken after the regime switching depends on the four components of the environment variable. We note that this value may be unchanged for some variables, as observed for example for the hub (gold) during the first three periods described above, or for the core between the second and third periods (Sterling), but that their jumps are always simultaneous. Based on observation of IMS developments over the last century and a half, the geopolitical $W_t$ and regulatory $R_t$ components of the environment variable are the only threshold variables in the model. Along with the technological $T_t$ and institutional $I_t$ components, they condition the values taken after the regime change by the core, the hierarchy of distances, and the coefficient of global distances.

Apart from regime switchings, the hub, distance hierarchy and overall distance coefficient are stable.

## 3.3 International financial system

Like those of the IMS layer, the three characteristics of the IFS layer (see Figure 13) are described by three specific matrices: the adjacency matrix $A_F$ describes the position of the edges and thus designates the hub, as the most connected financial center; and the core, as local hubs. The hierarchical distance matrix $\mathscr{D}_{\text{F}}$ describes the hierarchy of distances from each node to the hub, and the final distance matrix $D_F$ describes the length of the edges and thus characterizes the extension of the network. The combination of those two distance matrices characterizes global distances within the layer. In other terms, based on the previously reviewed theoretical and empirical literatures both in monetary and financial economics and in complex networks, the core of the IFS layer is defined by its connectivity, unlike the IMS layer where it is defined by its short distance from the hub. All three matrices are square matrices of dimension $n \times n$. The indexing is similar to that of the IMS layer matrices, except that it starts at 1 (i.e. $i = 1, \dots, n$), with the graph including only countries (financial centers), whereas the graph of the IFS layer includes in addition to countries (currencies), the reference asset underlying confidence in the system, indexed 0. Countries $C_1, \dots, C_n$ are indexed in the same order than that of the IMS layer.

### 3.3.1 Adjacency matrix

The structure of the adjacency matrix $A_F$ is as follows, in the example where the financial center indexed $i = n - 1$ is the hub, and $i = n$ is the core to which $i = 2$ is directly linked:

$$A_F = \begin{array}{c} \\ \rotatebox{90}{i=1,...,n} \end{array} \overset{i=1,...,n}{\begin{pmatrix} 0 & 0 & ... & 0 & 1 & 0 \\ 0 & 0 & ... & & 0 & 1 \\ ... & ... & 0 & 0 & 1 & \\ 0 & & 0 & 0 & 1 & ... \\ 1 & 0 & 1 & 1 & 0 & 1 \\ 0 & 1 & & ... & 1 & 0 \end{pmatrix}} \tag{11}$$

As before, the network is undirected and the $A_F$ matrix, like the other two matrices describing the IMS structure, is symmetrical. Unlike the IMS, where the underlying asset of confidence is added to the currencies in the graph and is always indexed 0, in the case of the IFS, the adjacency matrix is not unchanged over time: the financial center $C_k$ that constitutes the hub is not always the same, and its indexation $k_t$ can in principle correspond to any value in the interval $1, ..., n$, i.e. all the financial centers in the system. In practice, the period under study shows only two: London and New York. The same applies to the financial center(s) $C_{k_1}$, $C_{k_2}$, etc., which form the core: any financial center can in principle become the core or part of it when a regime switching occurs. Over the period studied, the core is composed of London as the sole secondary hub during the Interwar and Bretton Woods eras; and several financial centers in the periods of strong financial integration represented by the 1st and 2nd eras of globalization.

The assumption that any financial center can, in principle, become the hub or the core following a regime change is aimed to keep the model as general as possible, so that it can be used to study earlier systems, or the prospects for the current system. Within this general framework, on the basis of the evolutions of the IMS and IFS described in Sections 1 to 3 and the literature on currency dominance, we hypothesize that the IFS hub corresponds to the currency or one of the currencies of the IMS core, i.e. $d_{M\ k,0\ t} = \underline{d}_M$. In view of the same facts and literature, a financial center belonging to the IMS core is a necessary condition for it to be an IFS hub, but not necessarily for it to belong to the IFS core.

So, nodes connected to the hub via the core node $C_{k_1}$ being denoted $C_{k_{1_a}}$, $C_{k_{1_b}}$, etc., the edges connecting the hub are described by:

$$\begin{gathered} a_{F\ i,j} = 1 \text{ if } i = k \text{ or } j = k \text{ and } i,j \neq k_{1_a}, k_{1b}, ...,\ (i,j) \neq (0,0) \\ a_{F\ i,j} = 0\ \forall\ i \neq k \text{ or } j \neq k \\ \text{with } k\ / d_{M\ k,0\ t} = \underline{d}_M \end{gathered} \tag{12}$$

and the edges connecting core $k_1$ by:

$$a_{F\ i,j} = 1 \text{ if } i = k_1 \text{ and } j = k_{1_a}, k_{1_a}, ...; \text{or } i = k_{1_a}, k_{1_a}, ...\ ; \text{and } j = k_1 \tag{13}$$

The same applies if the core is made up of several nodes $k_1$, $k_2$, etc. There are no other edges in the adjacency matrix: all other values in the adjacency matrix are therefore zero.

When a regime switching occurs, the financial centers that constitute the hub and the cores are likely to change, as follows:

$$\begin{gathered} (C_{F\ k,t}, C_{F\ k_{1,t}}, C_{F\ k_{2,t}}, ...) = f_F\left(T_t, I_t, W_t, R_t\right) \\ C_{F\ k,t} = \{C_1, ..., C_n\ /\ d_{M\ k,0\ t} = \underline{d}_M\} \\ C_{k_{1,t}},\ C_{k_{2,t}}, ... = \{C_1, ..., C_n\} \end{gathered} \tag{14}$$

The non-linear form of function $f_F\left(T_t, I_t, W_t, R_t\right)$ describing the evolution of $C_{F\ k,t}$ and the $C_{k_{1,t}}$, $C_{k_{2,t}}$, ... with respect to the geopolitical $W_t$ and regulatory $R_t$ components of the environment variable is described in more detail below.

### 3.3.2 Hierarchical distance matrix

The hierarchical distance matrix $\mathscr{D}_{\mathrm{F,t}}$ establishes the hierarchy of distances corresponding to the edges of the adjacency matrix. Its structure is as follows, still in the example where the financial center indexed $i = n-1$ is the hub, and $i = n$ is the core to which $i = 2$ is directly linked:

$$\mathscr{D}_{F,t} = \underset{i=1,...,n}{} \overset{j=1,...,n}{\begin{pmatrix} 0 & 0 & ... & 0 & d_{F\ 1,k\ t} & 0 \\ 0 & 0 & ... & & 0 & d_{F\ 2,k_1\ t} \\ ... & ... & 0 & 0 & ... & \\ 0 & & 0 & 0 & & ... \\ d_{F\ k,1\ t} & 0 & ... & & 0 & d_{F\ k,k_1\ t} \\ 0 & d_{F\ k_1,2\ t} & & ... & d_{F\ k_1,k\ t} & 0 \end{pmatrix}} \tag{15}$$

$\mathscr{D}_{\mathrm{F,t}}$ describes the connexions to the hub and core(s) at time $t$ for non-zero elements of the adjacency matrix $A_{F,t}$:

$$
\begin{gathered}
d_{F\ i,k\ t} = d_{F\ k,i\ t} \\
d_{F\ i,k_1\ t} = d_{F\ k_1,i\ t} \\
d_{F\ i,k_2\ t} = d_{F\ k_2,i\ t} \\
\ldots \\
(d_{F\ i,k\ t}, d_{F\ i,k_1\ t}, d_{F\ i,k_2\ t}, \ldots) = g_F\left(T_t, I_t, W_t, R_t\right) \\
(d_{F\ i,k\ t}, d_{F\ i,k_1\ t}, d_{F\ i,k_2\ t}, \ldots) = \left\{\underline{d}_F, \overline{d}_F\right\},\ \forall i \neq 0 \\
\underline{d}_F \in [\underline{d}_{Fl}, \underline{d}_{Fu}] \\
\overline{d}_F \in \left[\overline{d}_{Fl}, \overline{d}_{Fu}\right] \\
\text{with } 0 < \underline{d}_{Fl} < \underline{d}_{Fu} < 1 < \overline{d}_{Fl} < \overline{d}_{Fu} < 1
\end{gathered}
\tag{16}
$$

The distance of financial center $i$ to the hub $d_{F\ i,k\ t} = d_{F\ k,i\ t}$, or the distance $d_{F\ i,k_1\ t} = d_{F\ k_1,i\ t}$ to the core $k_1$ in the case where it is not directly connected to the hub, is established in two possible intervals. $\underline{d}_F$ characterizes distances within the interval $[\underline{d}_{Fl}, \underline{d}_{Fu}]$. The financial centers characterized by these short distances are closely connected to one of the dominant financial centers, i.e. are themselves important in the operation of the IFS. $\overline{d}_F$ characterizes long distances within the interval $\left[\overline{d}_{Fl}, \overline{d}_{Fu}\right]$. The financial centers characterized by these long distances are remote from the dominant centers.

Note that the core of the IFS layer is defined by its connectivity, *i.e.* more than one edge in the adjacency matrix, unlike the IMS layer where it is defined by its small distance from the hub. In other words, $d_{F\ k,k_1\ t} = d_{F\ k_1,k\ t}$ does not necessarily belong to the interval $[\underline{d}_{Fl}, \underline{d}_{Fu}]$.

When a regime switching occurs, the hierarchical structure of distances, and therefore the financial centers in the close neighborhood of dominant centers, is likely to change. In the absence of regime switching, the hierarchical distance matrix remains unchanged from one period to the next.

### 3.3.3 Final distance matrix

The final distance matrix $\mathrm{D_{F,t}}$ describes the extension of the IFS layer. This dimension depends on the hierarchy established in the hierarchical distance matrix $\mathscr{D}_{\mathrm{F,t}}$, and on a global distance coefficient $\gamma_t$ that is high when transaction costs are high and low when transaction costs are low, i.e. the following structure:

$$
\mathrm{D_{F,t}} = \gamma_{Ft}\mathscr{D}_{\mathrm{F,t}} \tag{17}
$$

$$
\mathscr{D}_{F,t} = \underset{i=1,...,n}{\overset{j=1,...,n}{\begin{pmatrix} 0 & 0 & ... & 0 & \gamma_{Ft} d_{F\ 1,k\ t} & 0 \\ 0 & 0 & ... & & 0 & \gamma_{Ft} d_{F\ 2,k_1\ t} \\ ... & ... & 0 & 0 & ... & \\ 0 & & 0 & 0 & & ... \\ \gamma_{Ft} d_{F\ k,1\ t} & 0 & ... & & 0 & \gamma_{Ft} d_{F\ k,k_1\ t} \\ 0 & \gamma_{Ft} d_{F\ k_1,2\ t} & & ... & \gamma_{Ft} d_{F\ k_1,k\ t} & 0 \end{pmatrix}}} \tag{18}
$$

$$
\begin{array}{r}
\gamma_{Ft} = h_F \left(T_t, I_t, W_t, R_t\right) \\
\gamma_{Ft} = \left\{\underline{\gamma}_F, \overline{\gamma}_F\right\} \\
\underline{\gamma}_F \in \left[\underline{\gamma}_{Fl}, \underline{\gamma}_{Fu}\right] \\
\overline{\gamma}_F \in \left[\overline{\gamma}_{Fl}, \overline{\gamma}_{Fu}\right] \\
\underline{\gamma}_{Fl} < \underline{\gamma}_{Fu} < \overline{\gamma}_{Fl} < \overline{\gamma}_{Fu}
\end{array} \tag{19}
$$

The $\gamma_{Ft}$ coefficient is set in two possible ranges. $\underline{\gamma}_F$ corresponds to a low value, in the $\left[\underline{\gamma}_{Fl}, \underline{\gamma}_{Fu}\right]$ range. This interval corresponds to low transaction costs in the context of a low level of regulation of financial activity, i.e. short distances and a dense network, as in the 1st and 2nd eras of globalization. $\overline{\gamma}_F$ corresponds to a high value, within the interval $[\overline{\gamma}_{Fl}, \overline{\gamma}_{Fu}]$, in the context of a high level of regulation, as in the Interwar and Bretton Woods eras. This interval corresponds to high transaction costs under a high level of regulation of financial activity, i.e. long distances and an extensive network. When a regime switching occurs, both the $\gamma_{Ft}$ coefficient and the hierarchical distance structure are likely to change at the same time. In the absence of a regime switching, the $\gamma_{Ft}$ coefficient and the hierarchical structure are unchanged from one period to the next.

#### 3.3.4 Regime switchings

The regime switching of the IFS layer is therefore described as follows:

$$
\text{if}\left\{\begin{array}{c} W_t - W_{t-1} \geq W^* \\ \text{or } R_t - R_{t-1} \geq R^* \end{array}\right. \Rightarrow \left\{\begin{array}{c} (C_{F\ k,t}, C_{k_{1,t}},\ C_{k_{2,t}}, ...) = f_F \begin{pmatrix} T_{it} \\ I_{it} \\ W_{it} \\ R_{it} \end{pmatrix} \\ \\ (d_{F\ i,k\ t}, d_{F\ i,k_1\ t}, d_{F\ i,k_2\ t}, ...) = (d_{F\ k,i\ t}, d_{F\ k_1,i\ t}, d_{F\ k_2,i\ t}, ...) \\ = g_F \begin{pmatrix} T_{it} \\ I_{it} \\ W_{it} \\ R_{it} \end{pmatrix} \forall i = 1, ..., n \\ \\ \gamma_{Ft} = h_F\left(S_t\right) = h_F \begin{pmatrix} T_{it} \\ I_{it} \\ W_{it} \\ R_{it} \end{pmatrix} \end{array}\right.
$$

$$
\text{if}\left\{\begin{array}{c} W_t - W_{t-1} < W^* \\ \text{and } R_t - R_{t-1} < R^* \end{array}\right. \Rightarrow \left\{\begin{array}{c} (C_{F\ k,t}, C_{k_{1,t}},\ C_{k_{2,t}}, ...) \\ = (C_{F\ k,t-1}, C_{k_{1,t-1}},\ C_{k_{2,t-1}}, ...) \\ \\ (d_{F\ i,k\ t}, d_{F\ i,k_1\ t}, d_{F\ i,k_2\ t}; ...) \\ = (d_{F\ i,k\ t-1}, d_{F\ i,k_1\ t-1}, d_{F\ k_2,i\ t}, ...) \\ \forall i = 1, ..., n \\ \\ \gamma_{Ft} = \gamma_{F\ t-1} \end{array}\right. \tag{20}
$$

The regime switching of the IMS and IFS layers is simultaneous and associated with the crossing of the extreme event threshold $W^*$ for the geopolitical component $W_t$ of the environment variable (respectively, with the threshold $R^*$ for the regulatory component $R_t$). This regime switching causes a jump in the financial centers constituting the hub $C_{F\ k,t}$ and the core $C_{k_1},\ C_{k_2},\ ...$; and in the hierarchy of distances $(d_{F\ i,k\ t}, d_{F\ i,k_1\ t}, d_{F\ i,k_2\ t}, ...) = (d_{F\ k,i\ t}, d_{F\ k_1,i\ t}, d_{F\ k_2,i\ t}, ...)$ and the $\gamma_{Ft}$ coefficient of overall distances, associated to the level of transaction costs.

For each of these variables, the value taken after the regime switching depends on the four components of the environment variable. As for the IMS layer, this value may be unchanged for some variables, as observed for example for New-York as the hub of the last three periods, or for London as the core of the second and third periods. The global distance coefficient is also unchanged (and high) between the second and third periods. Apart from regime changes, the hub, core and global distances are stable.

### 3.4 Discussion

The hypotheses derived from the analogy allow us to propose an original theoretical model of the long-term developments in the international monetary and financial systems. The period discussed in the previous sections goes back to the last century and a half, but the theoretical model is sufficiently general to be used over a longer period, or for prospective analysis. All the model assumptions can be tested. The existing literature documents that time series (in particular, of prices and trade volumes) associated with each of the multiplex layers allow to produce an empirical measure of their hub, core and distance characteristics. The empirical validation of the model could, then, follow three main stages.

The first step is to validate the nature of the regime-switching model. On the basis of the stylized facts and reference literature, we propose a model with stable regimes and simultaneous regime switchings in the network structures of both layers. It should be noted that the multiplex actually enables the study of doubly simultaneous regime shifts: for each of the layers, and for the three variables describing the network structures within layers. The second stage of empirical validation would consist in defining a set of proxies for the components of the environment variable, and checking that the crossing of thresholds for the geopolitical and regulatory components is indeed associated with regime switchings in the multiplex. The third step would consist in implementing non-linear regressions to characterize the relationship between the components of the environment variable and the hub, core and layer structure variables.

The empirical validation would then enable us to gain additional understanding of the determinants of long-term trends in the simultaneous structures of the IMS and IFS, particularly with regard to dominant currencies and financial centers. It would also be possible to build *scenarii* of future developments. For example, on the basis of different evolutions in the components of the environment variable that are deemed plausible, the empirical estimation of the model parameters would make it possible to document, in an original way and taking into account the non-linearities of the underlying model, different *scenarii* for the dominance of the US dollar.

# 4 Calibration

### 4.1 Environment variable

In this section, we present a calibration exercise of the theoretical model with the dual aim of controling the ability of specific forms of the general functions previously described in Section 3 to reproduce the historical evolutions described in Section 2; and enabling to propose simulations of the sytem future evolution. As shown in Figure 14(a), the environment variable has three dimensions: a temporal dimension, a country dimension, and a dimension corresponding to the nature of the shocks.

The sequence of the calibrated model is based on the four homogeneous periods described above, each of which is decomposed into three sub-periods broadly corresponding to decades.

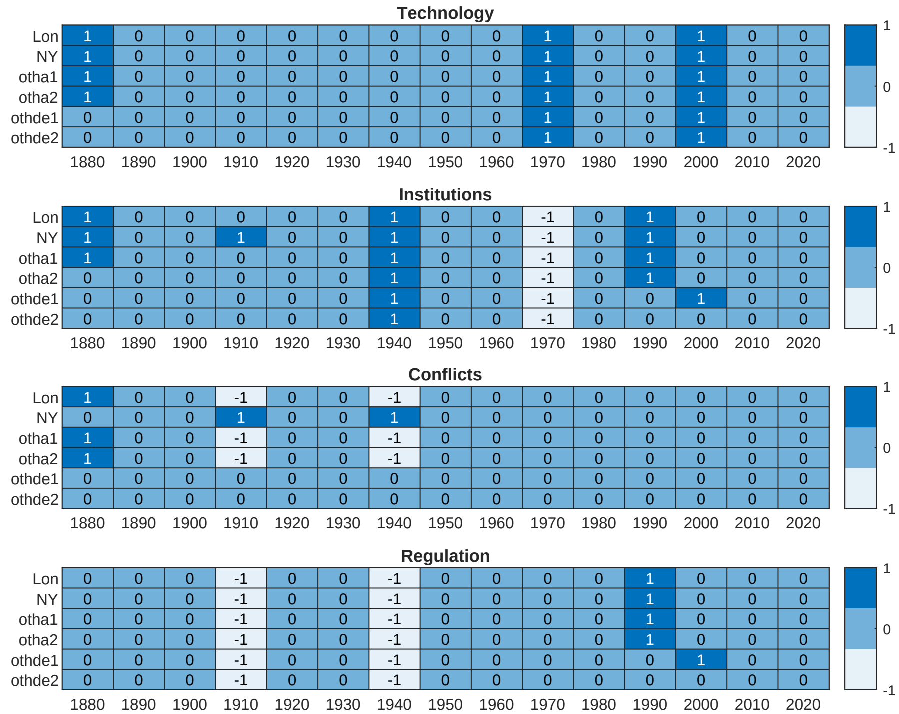



Figure 14: Summary table of the components of the environment variable used for the calibration. (+1) corresponds to an event of exceptional importance, favorable to the dominance of the country; and vice versa for (−1). (0) corresponds to the absence of an event of exceptional importance.

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A "contemporary" period describing the last two decades is added to the four periods previously described. This allows us to homogenize the length of the periods, but also to take into account the existence and effects of specific shocks on the technological, institutional and regulatory components of the environment variable that specifically occurred in the most recent period. Calibration is carried out for a stylized system restricted to 6 countries: the United Kingdom ("London"), the United States ("New-York"), two advanced economies ("other advanced 1", "other advanced 2") and two developing or emerging economies ("other developing and emerging 1" and "other developing and emerging 2"). For the present calibration, which is an illustration of the theoretical model and not an empirical validation, the elements of the environment variable exclusively take the values −1, 0 and +1. +1 corresponds to an event of exceptional magnitude, favorable to the dominance of the country, for the corresponding component of the environment variable. −1 corresponds to and unfavorable event of exceptional magnitude. 0 correspond to no exceptional event, either favorable or unfavorable.

The events coded on the basis of the sequence described in Section 2 are as follows, for the four components of the environment variable.

1. For Technology: the Industrial Revolution and the establishment of transatlantic ca-

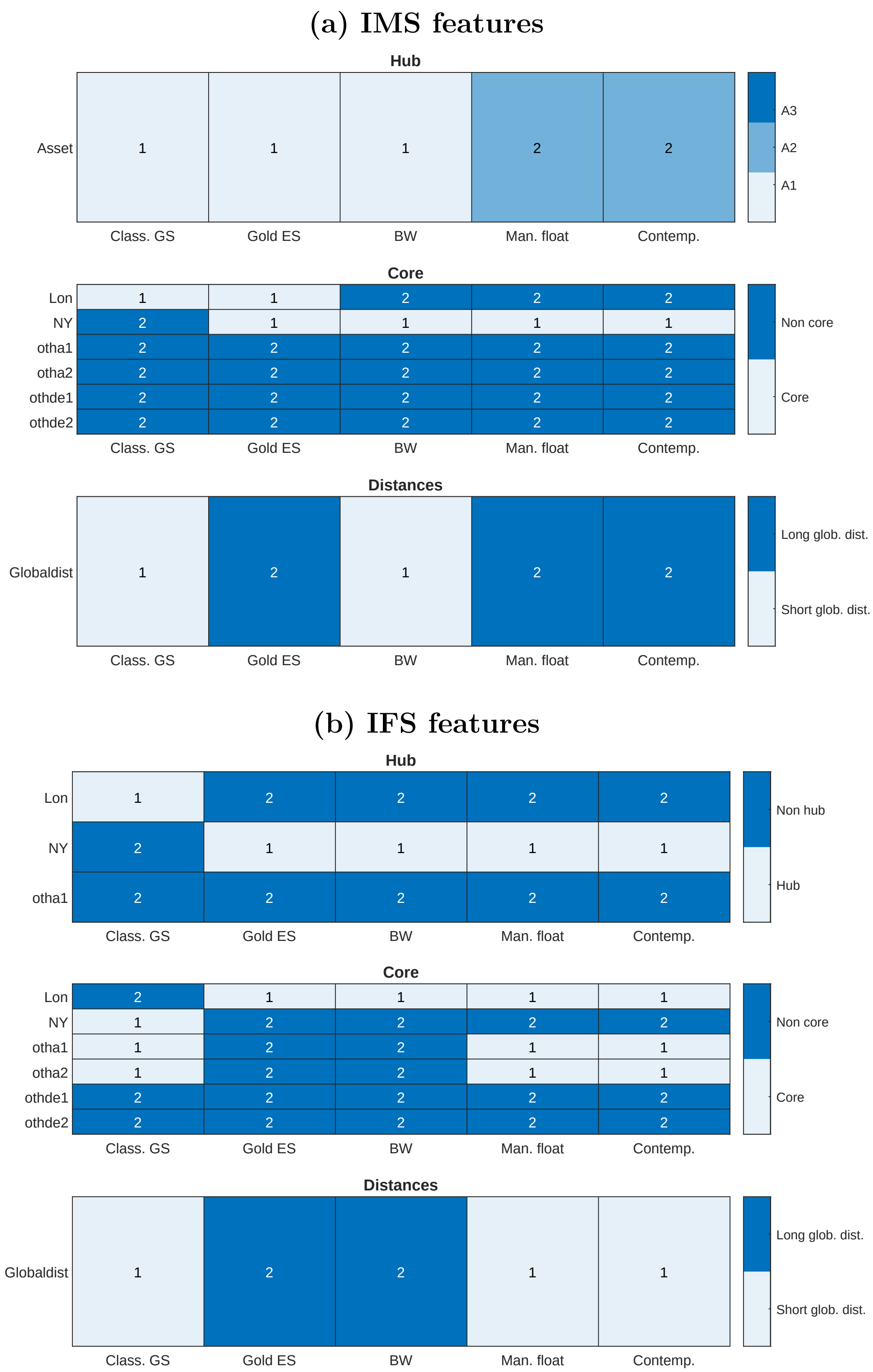


Figure 15: Summary tables of the states of the IMS (lower panel) and IFS (upper panel) features : Hub, Core, Distances. "othad1", "othad2", "othde1" and "othde2" respectively correspond to the two undefined advanced economies, and the two undefined developing economies of the calibration.

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bles for the Classical Gold Standard; the computerization of financial transactions for the post-BW; the advent of high-frequency technologies for the Contemporary period. These events are all favorable. The technological component of the environment variable therefore takes only two possible values: 0 and +1;

2. For Institutions: early inherited financial development for the Classical Gold Standard; the establishment of the Federal Reserve in the USA for the Gold Exchange Standard; the Bretton-Woods exchange rate system; the end of the Bretton-Woods system and then inflation targeting in advanced economies for the post-Bretton-Woods; and inflation targeting in developing and emerging economies for the Contemporary period. For the same reason as above, the institutional component of the environment variable takes the values 0 and +1 with the exception of the end of the Bretton-Woods system;

3. For Geopolitics and Conflicts, the climax of colonial empires for the Classical Gold Standard (favorable to the dominance of countries holding colonial empires); World War I for the Gold Exchange Standard, and World War II for Bretton-Woods (unfavorable for the initial main belligerents, favorable for the United States);

4. For Regulation, a restrictive shock for the Gold Exchange Standard, a second restrictive shock for Bretton Woods (unfavorable for all countries); deregulation in advanced economies for the post-Bretton-Woods era, and deregulation in advanced and emerging economies for the Contemporary period (favorable for the countries concerned).

## 4.2 Calibration: IMS

For the IMS, the system states to be reproduced by calibration are shown in Figure 15(a). Since they are assumed to be stable within each period, sub-periods are not shown. The hub is described by a single time series taking the values 1 (asset $A1$), 2 (asset $A2$) or 3 (asset $A3$). Here, $A1$ represents gold, $A2$ the credibility of monetary policy and $A3$ another non-determined asset, to keep the model as general as possible, and in particular to take into account the possible emergence of new forms of monetary organization. The core is described by one time series per country, taking the values 1 (core) or 2 (non-core). This choice allows us to take into account the possibility of several currencies belonging simultaneously to the core. Lastly, distances are described by a single time series taking the values 1 (short distances) or 2 (long distances). As emphasized previously, this simplified representation allows us to describe the entire structure of the graph: the hub, the hierarchy of distances between core and non-core, and the extent of the graph.

The environment variable determines successive states of the IMS system *via* conditional Markov chains. We define six conditional Markov chains describing regime switchings of the IMS. In what follows, we present the transition matrices. The corresponding chains are shown in Figure 16 . The hub states are determined by the first conditional chain ($P_h$, Figure 16(a)). The hub can have three states: $A1$, $A2$, and $A3$. When asset A1 experiences a major adverse shock to the institutional component in the first sub-period of the current period, and asset A2 experiences a major favorable shock to the same component in one of the sub-periods of the same period, the transition matrix describes a convergence of the system states towards $A2$. It is sufficient for the two shocks to occur in a majority of economies (i.e., here, four economies). When these conditions are not validated, the hub state remains unchanged. Matrix $P_h$ is calibrated as follows:

$$P_h = \begin{bmatrix} 0.1 & 0.9 & 0 \\ 0 & 1 & 0 \\ 0 & 0.9 & 0.1 \end{bmatrix} \tag{21}$$

The core states are determined by the second, third and fourth conditional chains ($P_{c1}$, $P_{c2}$, $P_{c3}$, Figures 16(b) to (d)). Each country can have four states: "core", "declining core", "non-core", and "ascending core". This choice of modeling sub-configurations of the core makes it straightforward to take into account the previous states of the system. When the country experiences a major adverse shock to the conflict component ($P_{c1}$, Figure 16(b)), the transition matrix describes a convergence of system states towards the declining core and non-core states. When the country experiences a major favorable shock to the conflict component ($P_{c2}$, Figure 16(c)), the transition matrix describes a convergence of system states towards the ascending core and core states. Finally, when the country experiences a major favorable shock to both the conflict and institutional components ($P_{c3}$, Figure 16(d)), the transition matrix describes an enhanced convergence of system states towards the ascending core and core states. When these conditions are not validated, the core states of the countries remain unchanged. Matrices $P_{c1}$, $P_{c2}$ and $P_{c3}$ are calibrated as follows:

$$P_{c1} = \begin{bmatrix} 0.1 & 0.8 & 0.1 & 0 \\ 0 & 0.5 & 0.5 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0.9 & 0.1 \end{bmatrix}, \qquad P_{c2} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0.5 & 0.5 & 0 & 0 \\ 0 & 0 & 0.9 & 0.1 \\ 0.9 & 0 & 0 & 0.1 \end{bmatrix}, \qquad P_{c3} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0.9 & 0.1 & 0 & 0 \\ 0 & 0 & 0.1 & 0.9 \\ 0.9 & 0 & 0 & 0.1 \end{bmatrix} \tag{22}$$

Finally, the states of distances are determined by the fifth and sixth conditional chains ($P_{d1}$, $P_{d2}$, Figures 16(e) to (f)). Distances can have two states: "long", and "short". When the system experiences a major adverse shock to the regulatory or institutional component ($P_{d1}$, Figure 16(e)), the transition matrix describes a convergence of system states towards the long distances state. When the system experiences a major favorable shock to the institutions component ($P_{d2}$, Figure 16(f)), the transition matrix describes a convergence of system states towards the short-distance state. As for the hub, it is sufficient for the shocks to occur in a majority of economies (i.e., here, four economies). When these conditions are not validated, the distances feature state remains unchanged. Matrices $P_{d1}$ and $P_{d2}$ are calibrated as follows:

$$P_{d1} = \begin{bmatrix} 0.1 & 0.9 \\ 0 & 1 \end{bmatrix}, \qquad P_{d2} = \begin{bmatrix} 1 & 0 \\ 0.9 & 0.1 \end{bmatrix} \tag{23}$$

Running 1000 iterations of this system using Monte Carlo simulations produces the states shown in Figure 17(a). As the Markov chain is a stochastic process, the result is in the form

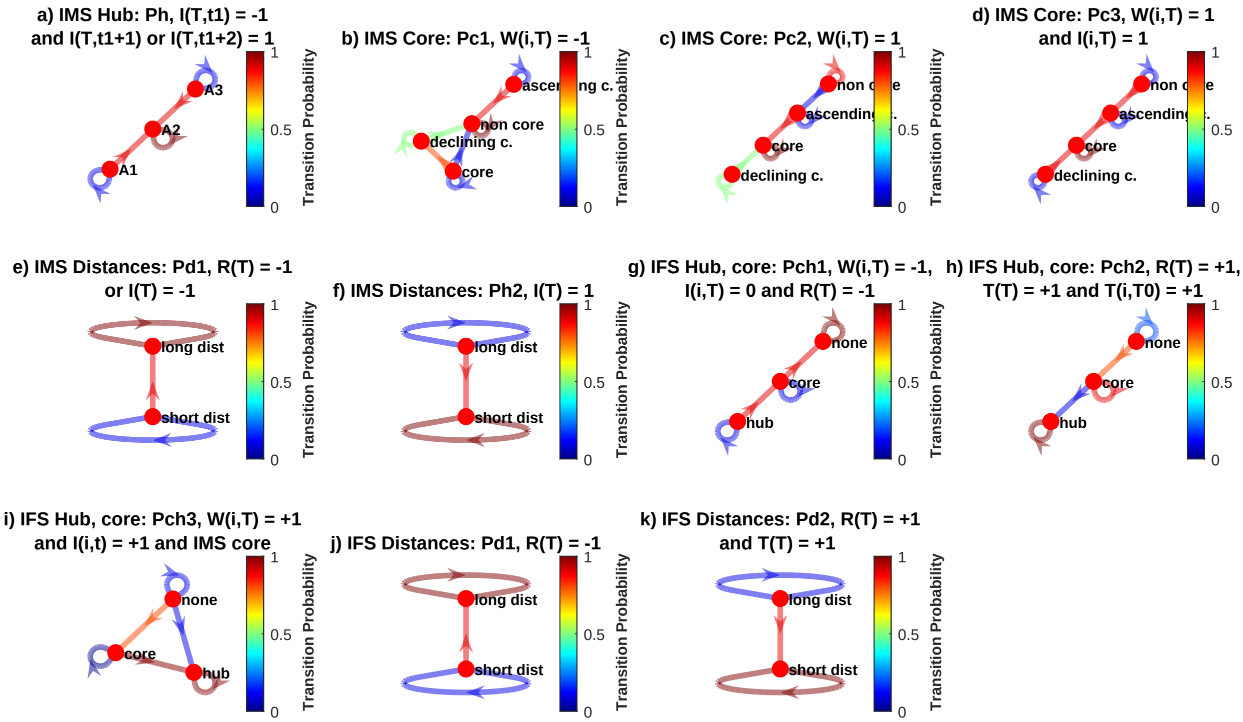


Figure 16: Conditional Markov of IMS and IFS features regime switchings. Each panel represents a conditional Markov chain. The country index $i$ is omitted when the condition concerns the majority or all countries. Nodes represent system states. Arrows pointing from one state to another represent the direction of transition. The color of the arrow represents the probability of transition, from 0 (dark blue) to 1 (dark red). Self-loops around a state represent a transition from one state to itself. For example, on the second panel (first row, second column), which describes the evolution of the IMS core state of a country belonging to the initial belligerents in a conflict, if the country is initially "IMS core", its state generally transitions to "IMS declining core" (red directed arrow), and marginally to "IMS non-core" or "IMS core" (dark blue directed arrows).

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of frequencies rather than single states. Width of the lines represents the frequency of the different states of the IMS features in the simulations. The calibrated model satisfactorily reproduces the observed dynamics. In particular, the states of London and New-York as cores are satisfactorily described: London evolves from core (first period) to declining core (second period) then declining core / non-core (latest periods). In parallel, New York evolves from non-core (first period) to ascending core (second period) then core (latest periods).

## 4.3 Calibration: IFS

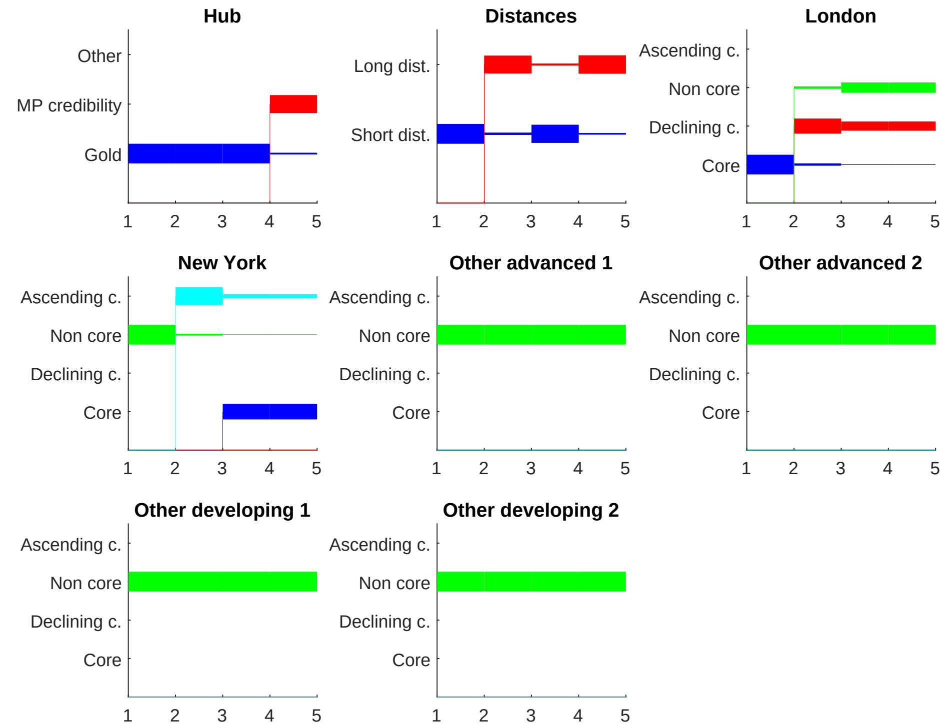
For the IFS, the system states to be reproduced by calibration are shown in Figure 14(b). The hub is described by a single time series taking the values 1 (hub) or 2 (non-hub). The core is described by one time series per country, taking the values 1 (core) or 2 (non-core). This choice allows us to take into account the possibility of several financial centers belonging simultaneously to the core. Lastly, distances are described by a single time series taking the values 1 (short distances) or 2 (long distances).

The environment variable determines successive states of the IFS system *via* conditional Markov chains. We define five conditional Markov chains describing regime switchings of the IFS. In what follows, we present the transition matrices. The corresponding chains are shown in Figure 16. The hub and core states are jointly determined by the first three conditional chains ($\mathscr{P}_{ch1}$, $\mathscr{P}_{ch2}$ and $\mathscr{P}_{ch3}$, Figure 16(g) to (i)). The joint determination of hub and core is possible in the case of IFS because the assets that form them are of the same nature: both are financial centers. This is not the case with IMS, where the hub is the asset that underlies confidence in the system, and therefore cannot be one of the currencies.

Financial centers can have three states: "hub", "core", and "none". When a financial center experiences an unfavorable shock to both the conflict and regulation components ($\mathscr{P}_{ch1}$, Figure 16(g)), the transition matrix describes a convergence of system states from hub to core state and from core to none state. When a financial center experiences a favorable shock on both the regulatory and technological components, with the initial shock on the technological component being favorable (countries with early financial development) ($\mathscr{P}_{ch2}$, Figure 16(h)), the transition matrix describes a convergence mainly towards the core state. Finally, when the country experiences a major favorable shock to both the conflict and institutional components and belongs to the IMS core ($\mathscr{P}_{ch3}$, Figure 16(i)), the transition matrix describes a convergence of system states towards the core and then hub states. When these conditions are not validated, the hub and core states of the countries remain unchanged. Matrices $\mathscr{P}_{ch1}$, $\mathscr{P}_{ch2}$ and $\mathscr{P}_{ch3}$ are calibrated as follows:

$$\mathscr{P}_{ch1} = \begin{bmatrix} 0.1 & 0.9 & 0 \\ 0 & 0.1 & 0.9 \\ 0 & 0 & 1 \end{bmatrix}, \qquad \mathscr{P}_{ch2} = \begin{bmatrix} 1 & 0 & 0 \\ 0.1 & 0.9 & 0 \\ 0 & 0.8 & 0.2 \end{bmatrix}, \qquad \mathscr{P}_{ch3} = \begin{bmatrix} 1 & 0 & 0 \\ 0.99 & 0.01 & 0 \\ 0.1 & 0.8 & 0.1 \end{bmatrix} \tag{24}$$

(a) IMS features




(a) IFS features

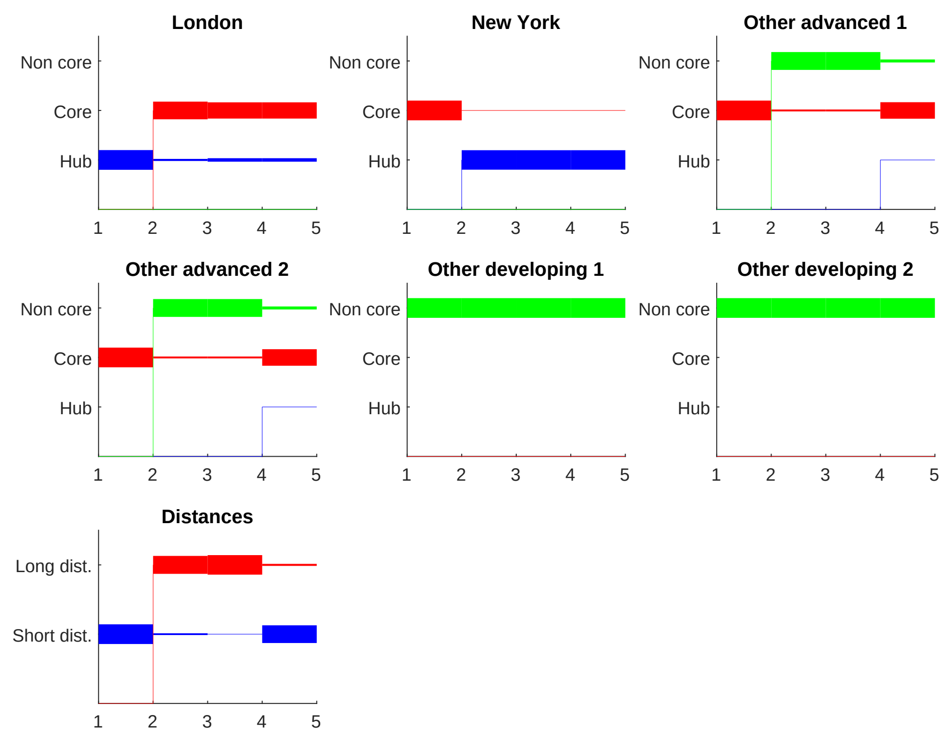



Figure 17: Simulation of the states of the IMS and IFS system. Monte Carlo simulations, 1000 iterations. Data points on the x-axis represent periods. Width of lines is proportional to the frequency of the corresponding state in the simulations.

Finally, the states of distances are determined by the fifth and sixth conditional chains ($\mathscr{P}_{d1}$, $\mathscr{P}_{d2}$, Figures 16(j) to (k)). Distances can have two states: "long", and "short". When the system experiences a major adverse shock to the regulatory component ($\mathscr{P}_{d1}$, Figure 16(j)), the transition matrix describes a convergence of system states towards the long distances state. When the system experiences a major favorable shock to the institutions and regulatory component ($\mathscr{P}_{d2}$, Figure 16(k)), the transition matrix describes a convergence of system states towards the short-distance state. As for the IMS, it is sufficient for the shocks to occur in a majority of economies (i.e., here, four economies). When these conditions are not validated, the distances feature state remains unchanged. Matrices $\mathscr{P}_{d1}$ and $\mathscr{P}_{d2}$ are calibrated as follows:

$$\mathscr{P}_{h1} = \begin{bmatrix} 0.1 & 0.9 \\ 0 & 1 \end{bmatrix}, \qquad \mathscr{P}_{h2} = \begin{bmatrix} 1 & 0 \\ 0.9 & 0.1 \end{bmatrix} \tag{25}$$

Running 1000 iterations of this system using Monte Carlo simulations produces the states shown in Figure 17(b). The calibrated model reproduces the observed dynamics. In particular, the financial center states are reproduced satisfactorily. London and New York mirror each other (hub then core, and core then hub, respectively). The other advanced economies appear as core at the beginning and end of the period under study, with a marginal evolution to hub at the end. As in the case of the IMS, other developing and emerging countries remain outside the core. In the system as defined, IMS core status is linked to an institutional environment consistent with the underlying asset of confidence (in other words, a specific central banking practice). From an IFS perspective, in particular, a prior financial development shock is required for core, and IMS core membership is required for hub. The non-linearity of the system reinforces the restrictive nature of these conditions. However, its apparent inertia should not be understood as immutability, particularly in a polycrisis environment, where moreover monetary and financial innovation tends to develop more rapidly in countries where initial financial development is lowest.

If we consider the system as a whole (IMS and IFS), this calibration highlights the main contribution of the model we are proposing, which is to describe changes in system state in a satisfactory way, based on a simple model of the system itself, reduced to a small number of stylized features; and of regime switchings, formalized as Markov chains conditional on the components of the environment variable.

# Conclusion: some lessons for the future from the analogy

It should be clear that we do not consider that the primarily deterministic character of the organization of stellar systems can strictly be transposed to the IMS/IFS, whose shapes depend on unpredictable human decisions. However, the analogy between Copernican-type stellar systems and IMS/IFS offers an interesting modelling approach. On the one hand, it provides a simple, stylized reading of monetary and financial history over a century and a half, offering a framework for prospective analysis. On the other hand, it allows us to describe the corresponding theoretical model in formal terms. This model, based on a novel combination of a multi-layer network and regime switching model related to a multi-dimensional environmental variable, is fully testable. A calibration using simple conditional Markov chains enables us to satisfactorily reproduce the dynamics of the system, in particular the dominance of currencies (IMS core) and marketplaces (IFS hub and core).

Beyond the model, by generalizing the analogy, three main lessons can be drawn. The first lesson is that the center of the system is not necessarily where we think it is. This first lesson, directly linked to the transition from the geocentric to the heliocentric model , echoes the main current, but also more recurrent, concerns regarding the structure of the IMS/IFS. More specifically, in the case of the IMS, we argue that the hub of the system is not one of the currencies, but the underlying asset of confidence. Under these conditions, the dominance of the US dollar in the IMS seems to be assured for the moment as currency dominance is essentially stable over long eras bounded by environmental shocks of exceptional magnitude. This does not mean that the future may not be different. In the case of the IFS, we agree with the work of economic historians who stress that, while persistence is a key feature of the system, it should not be overestimated (e.g., Eichengreen et al., 2018). The driving force behind the dynamics of financial integration is not necessarily solely the US. For example, financial integration has been driven by European integration since the 1950s.

The second lesson proceeds from a broad generalization of the analogy. So far, we have reasoned within the general pattern of a single heliocentric system. Modern astrophysics studies an infinite number of stellar systems. This would correspond to a strong form of multicentrism, describing systems operating essentially unrelated to each other as opposed to a weaker form of multicentrism, described by our proposed model, in which there may be secondary dominant currencies and financial centers, but within the same connected graph. The difference between the two is essential in assessing the emergence of the Remimbi in the IMS, for example. We can thus imagine that after the emergence of the currency as a regional hub in the IMS, the structure of the system could evolve towards a true multi-polarization with disconnected graphs.

The third and last lesson from the analogy is related to the fact that, in addition to the life cycles of stars, the dimensions of the universe radically change over time, with the Big bang, the expansion of the solar system, and eventually the contraction of the universe. As with multi-centrism, the variation over time of the system dimensions could then be understood in the sense of the medium term, as in our proposed model, which mimics the life cycle of stars. This reading corresponds with distances between the IMS currencies changing over time with the transaction costs associated with the nature of the exchange rate regimes, currency risk and interoperability of banking systems; and distances between financial centers of the IFS also evolving, along the U-shaped financialization curve (Obstfeld and Taylor, 2004; Bastidon et al., 2023). In the very long term, these variations do not exclude more radical variations corresponding to the overall dynamics of the capitalist system.

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