A Tale of Two Capitals

Modelling the Interaction between Ideas, Physical Capital, and Growth

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Abstract

This paper models the relationship between innovation and sustained economic growth through as being mediated by institutions that calibrate a 'structure of technological production' analogous to capital-based models of the structure of production. Our framework discusses two types of capital: physical capital and ethereal capital (productivity-enhancing ideas). We cast these two structures in a network, the structure of which is determined by the institutions of a society. Predictions derived from this model may resolve some puzzles in the history of economic growth, such as ancient inventions 'far ahead of their time' failing to stimulate sustained growth, the phenomena of simultaneous independent invention, and failures of technology transfers.

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1 Introduction

The economic and technological history of our world is full of puzzles that we struggle to explain. Economists and social scientists have proposed various theories to explain economic development by answering at least one of the following three questions: Why did sustained economic growth *not* start until around the year 1800? Why did sustained economic growth originate only in Northwest Europe? Why are there variations in income per capita around the world today? A large variety of answers have been proposed that variously emphasize the role of geography, factor endowments, genetic inheritance, capital accumulation, knowledge accumulation, scientific networks, rhetorical and cultural attitudes, and institutions and incentives. While it would be an impossible task to settle these debates in any satisfying way, we integrate several of these key insights into a framework of our own in order to explain three particular puzzles in the history of economic growth and technology.

First, when one looks across the ages, there are curious instances of men and women devising ingenious inventions and conjuring ideas "before their time." Some of these are captured in Hollywood movies that depict the famous person as having "modern" sensibilities or notions that tragically are not accepted as the norm in broader society at the time. Yet neither the supposed Ancient Greek "computers" nor Da Vinci's aerial helicopters spawned an Industrial Revolution in the Bronze Age or the Italian Renaissance in the way that Watt's steam engines did for 18th century England. If a Martian were to visit Earth in the year 1000, it would not bet on the warring tribal kingdoms of Europe to one day command global prominance, but perhaps Song China–with its sprawling urbanized empire replete with the scientific wonders of astronomy, gunpowder, and the printing press, or the Islamic Caliphates–in their "Golden Age" with their advanced knowledge of philosophy, astronomy, algebra, geometry, and medicine stored in Baghdad's House of Wisdom, among other centers of learning. Yet indeed it was "backward" Europe that would ultimately win the day, leading to one of the most persistent head-scratchers in social science (Rosenberg and Birdzell 1986, 9 and Ch.9; Diamond 1999).

Second, there seem to be specific times and places where ideas seem to "hang in the air," to be discovered simultaneously and independently–calculus by Leibniz and Newton, the airplane between the Wright Brothers and the Smithsonian, or marginal utility by Menger, Jevons, and Walras. Some such controversies extend into the present day, as scientists dispute the Nobel-prize-winning role of James Watson and Francis Crick in discovering the structure of DNA, (Pray 2008: 100).

Finally, as economists since Adam Smith have described, the only way to enhance income per capita is by increaseses in real productivity, a primary means to that end is the accumulation of capital. Growth models, from Harrod-Domar through Solow (1956) and Romer (1990), variously emphasize the key roles of physical capital, savings rates, human capital, and knowledge or "total factor productivity" in explaining variations in income per capita around the world. Yet economists have also documented that the solution is not as simple as high-income countries transplanting to low-income countries these key ingredients via foreign aid, technology transfers, or private investment, and expect economic growth.

This paper provides a framework to assist in resolving these puzzles, and provides a means of assessing the role of various factors that various literatures on economic growth. We develop a framework for understanding the entanglement between ideas, instutitions, and sustained long-run economic growth by integrating what we term "ethereal capital" into existing frameworks that explain the heterogenous structure of *physical* capital and its relationship to growth (fluctuations) (Hayek 1935; Garrison 2000). We highlight the modes of interaction between physical capital and intellectual capital, as well as the institutions that mediate the nexus of the two, and their critical role in allowing ideas to turn into sustained long-run economic growth. We cast both forms of capital into a network model, where agents can stochastically innovate new ethereal capital and imitate the ethereal capital of those around them. Differences in network structure, which is determined by the network rules (our operationalization of "institutions") affect how likely agents are to successfully imitate and interact with other agents, affecting economic growth for the society. We finally apply the framework to generate insights in explaining the three puzzles outlined above.

2 Theories of Economic Growth

As usual, one can begin with Adam Smith and the Classical economists. These political economists and moral philosophers, unburdened by the Procrustean pressures of formal modeling, spent as much of their focus on the art of institutions and ideas behind prosperous or impoverished societies as on the scientific analysis of the logical consequences of policy choices. Smith (1776) memorably describes the division of labor and capital accumulation as two key factors that explain the differences in the wealth of nations. As countries permit and develop new trading opportunities, this allows for greater specialization and exchange, learning by doing, and makes investment in specialized tools profitable. Young (1928) describes the process of increasing returns to scale for production as capturing Smith's insights about the division of labor being limited by the extent of the market. Bauer (2000) and Buchanan and Yoon (2000) pick up this thread to describe how economic growth is the long process of transforming production for subsistence to production for exchange, and how this generates increasing returns for the wider society, respectively.[1]

Economists began trying to formally model the process of economic development in the mid-20th century with growth theory models. The early Harrod (1939) and Domar (1946) model focused on the optimal marginal propensity to save and the capital to output ratio to determine an economy's growth rate along a "knife-edge equilibrium" growth path. While criticized for being simplistic, it was enormously influential on the field of development economics, as it emphasized the necessity of directing surplus resources into investment in order to attain a high growth rate (Easterly 2002, Ch. 2). The famous model of Solow (1956) recasts the Harrod-Domar model into a neoclassical framework, and to explain the key "stylized facts" of economic growth documented by Kaldor (1957). In the Solow model, the unique steady state equilibrium growth path of output per worker is determined by the stock of *physical* capital. Exactly how high the *level* of that growth path is, is determined by the (exogenously determined) growth of "technology" or "total factor productivity." Solow (1957) famously calculated that almost 90% of the economic growth from 1909-1949 came from growth in "total factor productivity," - famously called the "Solow residual," the unexplained exogenous part of Solow's model. Furthermore, a chief implication of the dynamics of Solow's model was that countries should *converge* over time, as due to the diminishing returns to capital, low-income countries with little capital should grow much faster than high-income countries with much capital, and "catch up" to the high-income countries. The empirical record for this has been mixed. Pritchett (1997) for example, famously demonstrated in the 1990s how wealthy countries have been *diverging* more than ever. However, recent work by Johnson and Papageorgiou (2018) suggest that *since* 1990, low-income countries have indeed been catching up and converging with high-income countries.

The focus on "capital fundamentalism" (Easterly 2002, Ch. 3) has caused some economists to turn to other models for explaining economic growth. In addition to *physical* capital, perhaps *human* capital, the skills and knowledge embodied in productive labor, is key. Hall and Jones (1999), for example show that even with human capital in the model, the vast majority of the productivity differences in their sample come from a "productivity residual" akin to

[1] See Gangotena and Safner (2019) for an extended discussion of the use and abuse of "increasing returns to scale" and production functions.

Solow's total factor productivity. Romer (1990) explicitly models "knowledge" as a nonrival input to the production process that can be explicitly invested in by profit-seeking firms. Endogenizing Solow's "total factor productivity," Romer argues that new knowledge (a non-rival input) is created by applying human capital (researchers) to the stock of all existing knowledge, and that new knowledge is embodied in human capital in manufacturing to yield higher growth in output per capita.

An alternative perspective on development comes from economists and economic historians that argue that it is primarily *institutions* that affect knowledge and incentives for socially productive exchange and investment. North (1990); North (1991), for example, describes the evolutionary processes of economic history as pervasive institutional changes that alter incentives for productive investment and trade. North and Thomas (1976) and Rosenberg and Birdzell (1986) describe the institutional transformations of Western Europe that allowed it uniquely to spawn the Industrial Revolution and maintain sustained economic growth. Baumol (1990) argues how institutions channel the natural entrepreneurial drive of individuals in different societies towards either productive or unproductive and destructive social outcomes. Acemoglu, Johnson, and Robinson (2001), Acemoglu, Johnson, and Robinson (2002), Acemoglu and Johnson (2005), Acemoglu and Robinson (2012) show that variation in the quality of economic, political, and social institutions explains much of the variation in modern economic development. Mokyr (1990); Mokyr (2003) specifically highlights the role of *science* and *scientific institutions* in spreading and exploiting new knowledge, such as the "republic of letters" that connected Northwestern Europe during the Industrial Revolution. Glaeser et al. (2004) are sympathetic to the view, but claim that it is empirically difficult to "measure" institutions, or operationalize measures of "good" institutions beyond mere policy choices and outcomes.

In contrast, McCloskey (2007, 2011, 2016) argues the critical role of ideas, and ideas alone, in shaping the Industrial Revolution and economic progress. She critiques "neo-institutionalism" as being unable to explain the origins of particular institutional changes that enhance growth, or how to properly create better institutions in a low-income society, beyond handwaving and incantations of "add (good) institutions and stir." Her books describe how it was unique cultural changes in attitudes in Western Europe that elevated the social status of merchants, commerce, and innovation, for the first time in history, allowing the institutional changes to facilitate more investment, innovation, and exchange.

2.1 Shortcomings of Existing Theories

While we are sympathetic to each view on various margins, in our opinion, each has significant shortcomings that our framework seeks to extend and remedy.[2] The formal growth theory models that focus on the accumulation of capital (physical or human) fail to fully explain the role of the technology or total factor productivity residual, which is empirically a very large part of the puzzle.

Endogenous growth theory models are a step in the right direction, but they are also constructed to achieve increasing returns and technological spillovers *by assumption*. For example, in Romer (1990), the stock of knowledge, A, is defined to grow proportionately to the level of its existing stock, $\dot{A} \propto A$, such that, the *larger* the existing stock of knowledge, the *faster* it grows into future periods. This is justified by *assuming* that because knowledge is non-rival, it cannot be fully appropriated by knowledge-producers, and will generate positive spillovers by various mechanisms (Arrow 1962a, 1962b). All of this *might* happen, but as we argue in Gangotena and Safner (2019), the increasing returns generated by knowledge come not from anything inherent to the production of knowledge (what we call "physical technology"), but rather from specific institutional contexts within which this production takes place (what we call "institutional technology"). The presence of technological spillovers implictly makes fundamental assumptions about the institutional network within which knowledge-producers produce and collaborate with others.

As such, we recognize that institutions are key to the linkage of physical capital and "knowledge," but the literature on institutions also has limitations. Glaeser et al. (2004) are correct to point out that existing measures for institutions are quite poor proxies that seem to measure the *results* of political decisions and policy *outcomes* more than something about "institutions" themselves. Mokyr (1990); Mokyr (2003) comes closest to operationalizing the role of a *network* of scientists to explain how sustained economic growth can emerge when thinkers and tinkerers collaborate and share knowledge amongst themselves.

Finally, the emphasis on cultural ideas and attitudes towards growth-enhancing activities in McCloskey's books deserves greater attention, but is not a formal or parsimonious explanation for where these ideas came or how they originate institutional change.

[2] This is not an exhaustive survey of the different theories explaining variations in economid development.

We believe there is a way to reconcile Solow-Romer's capital accumulation with North's institutional change and McCloskey's idea-driven progress. In doing so, we hope to shed some light on the several puzzles we have described.

3 The Dual Structure of Capital: Physical and Ethereal

We consider two orthogonal spaces that are necessary for augmenting labor in production: physical capital and "ethereal" capital. Each space is constituted by a network of heterogeneous, complementary components that form a specific structure that enhances productivity. The structure of each is governed by different dynamics, and the complex but necessary relationships between the physical and ethereal are mediated by a society's institutions. Before we describe our model, we explore the key similarities and differences in the structures of physical and ethereal capital.

3.1 The Physical Capital Structure

Economists and economic thinkers have attempted to model the structure of physical production since the beginning of economics as a distinguishable field of study. In addition to pioneering the study of the economy as a result of "human action but not of human design," the classical economists such as Adam Smith and especially David Ricardo formalized economic growth into a proto-stationary state model populated by rigid social classes: landowners, laborers, and capitalists. With the iron law of diminishing marginal returns to land, Ricardo gloomily forecasted that in the long run, wages and profits to capital would fall to subsistence levels, and rents to landowners would skyrocket.

Francois Quesnay's (1759) *Tableau Economique* famously depicts the flow of value through an economy's social classes: landowners, agricultural laborers, artisans, and merchants. Marx's *Das Kapital* (1867-1873) also reduced economic production to various socio-economic classes, the bourgeoisie capital-owners that extract surplus value from the working-class proletariat. Following the marginal revolution, big-picture models of economic growth fell out of fashion until Keynes (1936) revived the "circular flow" view of value through the economy. Leontief (1986) cast these into a formal input-output model that fixes the proportion of goods exchanged between nodes in the production process, represented as a matrix.

In contrast to these equilibrium models, a distinctly "Austrian" tradition of modelling the capital structure begins with Menger (1971), which categorizes economic goods into various "orders" based on their causal proximity in satisfying human desires. Goods of the first order * satisfy human wants, as a ready-made sandwich instantly satisfies a person's hunger. Goods of higher orders cannot directly satisfy human wants, but indirectly satisfy them by producing goods of successively lower orders. Thus, a hammer-factory produces hammers, which can be used to drive nails into a wall to hang a picture in person's house. The factory is removed from immediate consumption by three levels.

Bohm-Bawerk (1889) places this causal chain through time and describes the role of interest in coordinating this structure of production into more "roundabout" production processes that increase value and productivity, but require more investment in (higher-order) capital goods. Bohm-Bawerk explains his theory graphically with a series of concentric rings that depict the structure of production through time. The "bull's eye" is where production originates with basic land and labor in nature, and the roundabout production process emanates outward through time, as raw materials are transformed and value added at each stage, until the outermost ring provides direct value to consumers. Such a model helps explain why at any given period in an economy, different kinds of capital goods exist at different stages of production. Additionally, such a model facilitates both comparisons between different economies with different "ring structures," and also an exploration of the *dynamics* of changes - and how changes in interest rates and savings rates may cause reconfigurations in ring structures.

Hayek (1935) elaborates on Bohm-Bawerk's graphical representation of the capital structure with a triangle, with time on the horizontal axis and value on the vertical axis. Garrison (2000) further integrates them with the market for loanable funds and the tradeoff between saving and present consumption. Many economists in this Austrian tradition have utilized these models to model the dynamics of the boom and bust cycle – as the capital structure evolves in an inconsistent way (i.e. by monetary policy artificially altering interest rates, as is commonly argued), capital resources are misallocated, requiring painful capital restructuring, i.e. a recession.

The Hayek-Garrison representation of the capital structure has been tremendously productive as an instructive tool, thought it too has limitations. While its practitioners laudibly emphasize capital's heterogeneity, its multi-specific uses, and its complementarities (see e.g. Lachmann (1956)), the Hayekian triangle remains a highly-aggregated abstraction of an economy[3] arbitrarily carved up into stages of a single production process, directed by aggregated macroeconomic variables (e.g. "the savings rate" and "the interest rate" in the loanable funds market). Before we set forth our model, let us turn to the other type of capital and see how it is similar to physical capital, and then we shall combine both of them into our model.

3.2 The Ethereal Capital Structure

"Ideas" are combinatorial phenomena, where individual strings of thoughts from very disparate sources can be combined and woven together to create a new idea. As there are an uncountable multitude of thoughts, so there are further infinite combinations of these ideas such that no two ideas from different people are likely to be identical. However, there are significant overlapping patterns that are both distinguishable by their specific content, but similar enough in form or substance. For example, two authors could write a very similar story that uses similar tropes (e.g. boy meets girl, boy loses girl, boy regains girl). Or, two inventors could come up with a device that traps a mouse but each uses different materials and moving parts.

Ideas, or knowledge, cannot properly be considered goods in the traditional economic sense, as they are not subject to scarcity or other physical constraints. To develop a new idea contains no opportunity cost in the realm of ideas, as ideas are non-rival (that is, the development of one idea does not detract from other ideas), but *does* incur an opportunity cost in the physical realm as one directs scarce, rivalrous inputs with alternative uses towards producing a new idea. Time, labor, and any physical goods purchased and used (such as notebooks, instruments, or prototypes) are rivalrous and do have alternative uses. The abstract forms of songs are movies not scarce, but the compact disks and DVDs on which they are distributed and viewed are.

The unique thing about ideas is that they are nonrivalrous. Certainly, ideas can be made to be *legally* excludable by various institutions (such as patents and copyrights), and ideas that are "fixed in a tangible medium"[4] certainly become rivalrous, as only one person can physically possess a specific painting, book, or mousetrap at a time. However, with the above caveats, the essential component of ideas is that they are in part, nonrival. Thomas Jefferson (1813) memorably

[3] Though certainly better than a homogenous blob, K!

[4] This phrase describes the act sufficient for an artistic creation to obtain copyright in the United States, 17 U.S.C §101. See Safner (2016).

describes how:

> "He who receives an idea from me, receives instruction himself without lessening mine; as he who lights his taper at mine, receives light without darkening me. That ideas should freely spread from one to another over the globe, for the moral and mutual instruction of man, and improvement of his condition, seems to have been peculiarly and benevolently designed by nature, when she made them, like fire, expansible over all space, without lessening their density in any point, and like the air in which we breathe, move, and have our physical being, incapable of confinement or exclusive appropriation."

In order to better define something as abstract as "ideas," and to highlight the similar characteristics to the Austrian view of *physical* capital, we tentatively propose the term *"ethereal capital."*[5] Furthermore, we make several propositions about the structure of ethereal capital:

> **Proposition 1**: *ethereal capital is heterogeneous, combinatorial, and requires complementary physical and ethereal capital to improve productivity.*

The "structure" of the set of ideas available to society emerges as intellectual entrepreneurs combine various strings of thought to create original ideas. Ridley (2011 Ch. 1) memorably tells us that innovation occurs when "ideas have sex," and spawn *new* commercially-viable products:

> "the telephone [which] had sex with the computer and spawned the internet. The first motor cars looked as though they were 'sired by the bicycle out of the horse carriage'. The idea for plastics came from photographic chemistry. The camera pill is an idea that came from a conversation between a gastroenterologist and a guided-missile designer. Almost every technology is a hybrid."

For the limitless combinatorial possibilities of ideas to link to productive outcomes in the *physical* world, they must be linked through a genealogy of complementary ideas (and also to physical capital). If we may rule out mythical revelations or clairvoyance, one can only envision ideas and visions of the future built on the current stock of ideas today. Thus, while Da Vinci was able to tangibly perceive of a futuristic flying machine – it looked nothing like our aluminum body jet aircraft today – but a wooden, hand-powered, aerial screw, all ideas and resources available to the

[5] It also adds an air of mystery to the concept!

Italian Renaissance. It would take future work to develop the structure of complementary ideas, e.g. Newton's laws of motion, aerodynamics, and internal combustion engines, before a flying machine could take the physical form of the Wright Brothers' Flyer I in the early 20th century. In the case of the airplane, this requires the ideas such as the principles of motion, aeronautics, engineering, light aluminum building materials, and other "waypoint" technologies that make the conceptual into the practical.

Based on these ideas, entrepreneurs can choose to instantiate these ideas into real products. While ideas might be perceived as valuable for their own sake by intellectuals and those that live the life of the mind, ideas can only provide value to society when they are instantiated in products, organizations, or institutions that improve human welfare. Entrepreneurs of all stripes – in business, in government, in academia, can invest real (physical) resources to embody these ideas in the form of a new product, a new organization, or a new institution. This requires tradeoffs to be made between competing uses of physical resources.

How might we model the ethereal capital structure? A first interpretation of the structure of *ethereal* capital would be to apply the diagrammatic approach of Garrison (2000). Akin to the the triangles of Hayek (1935) triangles that link stages of production of physical goods from low-value, high-order goods through successive stages over time to higher-value, lower-order goods, we might consider a succession of stages that begin with low-value, highly-abstract ideas that extend through stages towards higher-value, less-abstract (more practical) ideas.[6] However, as documented by Kealey (1996); Kealey (2009), most cases of (commercially viable) inventions originate from practical tinkerers in their garages, rather than rigorous scientists researching in their labs. That is, the "linear" model from abstract scientific research to widespread practical technologies is incorrect. This myth, which originates with Bacon's (1620) *Organon*, is one that has served the intellectual and scientific elite, justifying public funding of science and the view of basic research as a public good, (Kealey and Ricketts 2014; Safner 2019).[7] Ridley (2011, 256) reminds us that

> "Newton had more influence on Voltaire than he did on James Hargreaves...[O]f the four men who made the biggest advances in the steam engine - Thomas Newcomen, James Watt, Richard Trevithick, and George Stephenson - three were utterly ignorant of scientific theories, and historians disagree about

[6] Hart (2015), building off of Fink (2015) and Leighton and Lopez (2013), discusses a possible structure of production of ideas from highest-order scholarship in universities through to first-order political implementation.

[7] We do not dispute the economic logic that scientific research may have positive spillovers, we only dispute the claim that abstract research is logically and temporally antecedent to discovery and invention.

whether the fourth, Watt, derived any influence from theory at all."

Most inventions were created before the scientific theories proving their viability were derived. Watt and Newcomen's steam engines were completed before the theory of thermodynamics. The "impossible engine" for spaceflight is working despite NASA's complete lack of understanding how or why it works.[8]

However, as we pointed out in the previous section, due to the limitations of the triangle-approach, we operationalize both the physical and the ethereal capital structure as a *network*.

The problem, as Hayek (1945) famously points out, is that useful knowledge is fragmented, tacit, and distributed across the minds of millions of people. It is of little use for a solipsist or a hermit, even if she is a genius, to contribute to economic growth. Likewise, even if the genius lives in the context of a broader society, like Archimedes or Leonardo, his or her contributions to the ethereal capital structure will fail to translate into economic growth without complementary physical capital and institutions that promote connections between physical and ethereal capital structures (like a "republic of letters").

4 Institutions-as-Network-Rules Interlink Physical and Ethereal Capital

We recast both the physical and ethereal capital structure not as a field, but as a network (Potts 2000). Each plan in the capital structure is in the mind of an individual, represented as a node in an interconnected network. In Gangotena et al. (2019), we operationalize *institutions as the rules that define the network structure.* Below, we outline our model in abstract to highlight the intuitions relevant for this paper and the puzzles the model can shed some light on.

Consider $N = \{n_t \in \mathbf{Z}_{++}\}$ nodes arranged on an undirected graph $G = (N, E)$. G is generated via a fully-connected Erdos-Renyi (ER) graph. For any individual agent i, the set of 1^{st} -degree neighbors is described by the set $N_i(E) = \{j : E_{ij} = 1\}$.

The population of agents in the model evolves according to the following dynamics:

1. An initial population of n_0 agents are initialized on the ER graph. At each time step:

[8] See http://www.physics-astronomy.com/2015/07/nasas-impossible-em-drive-works-german.html.

2. Agents are randomly born or die (are added to or removed from the network) at exogenous rates
   - Each agent is endowed with 1 unit of labor, and a random endowment $\in (0, 1)$ of physical capital and ethereal capital ("total factor productivity")[9]
3. Agents update their own etheral capital (TFP) by two mechanisms:
   - *"Innovation"*, where an agent comes up with a new idea that enhances their TFP by some scalar, according to a stochastic process
   - *"Imitation"*, where an agent copies the highest-value etheral capital (TFP) among its nearest neighbors with according to a stochastic process
4. Agents produce according to a uniform production function
5. Agents consume their production

The population dynamics evolve according to exogenously-determined birth and death rates. Random agents are selected to "die," and upon being selected, their edges with other agents are severed, and the physical capital of dead agents is distributed equally amongst the new agents "born" each period. "Newborn" agents inhereit "dead" agents' physical capital, and begin with the median population TFP (ethereal capital). For more on the formal model, including our chosen functional forms and exogenous parameters, see Gangotena et al. (2019).

The key feature of our model is that the growth of economy-wide ethereal capital (TFP) - and thus, economy-wide output per capita - is the sum of agents' innovations and imitation over time.[10]

$$E[\Delta A_{t,i}] = Innovation_{t,i} + Imitation_{t,i}$$

The key implication from this feature is that the ability for ethereal capital to productively grow (and as a result, the economy as well) depends on the *structure* of the network, which is our operationalization of "institutions." Since imitation is a key mechanism for how agents increase their ethereal capital (and innovation is random), the ability of agents to successfully improve their own ethereal capital by imitatation is an increasing function of the number of neighbors that they have in the network. An isolated agent with no neighbors has no ability to improve ethereal capital

[9] For the purposes of the model, Total Factor Productivity is synonymous with our interpretation of "ethereal capital."

[10] Following both exogenous and endogenous growth theory, A describes the stock of total factor productivity, or, in our interpretation, ethereal capital that enhances real productivity and output per capita.

by imitation, and must rely on innovation alone, whereas an agent in a densely connected network has a large set of innovations to draw upon and increase her own productivity.

This model improves upon existing endogenous growth models, as such models essentially "assume innovation."[11] Romer (1990), for example, assumes $\dot{A} \propto A$, that the stock of knowledge grows in proportion to the size of the stock of knowledge. The more existing knowledge that a society has, the fast its knowledge will grow, essentially getting increasing returns to growth by *assuming* that returns will increase. Furthermore, increases in knowledge, due to its non-rival nature, are assumed to spill over *instantaneously* and *uniformly* through the economy.

Instead, we believe that the change in knowledge (ethereal capital) is better understood to be dependent on the network structure:

$$\dot{A} \not\propto A; \quad \dot{A} \propto \text{Network structure}$$

Improvements to knowledge might be beneficial if and only if they can be disseminated and improved by other agents. This again is the difference between the genius hermit and Einstein, Watt, or Mozart connected to markets. In fact, as the population within the network grows, for some network structures, the growth rate of connections can be greater than the growth rate of the population, allowing *some* societies to escape the population dynamics of the Malthusian trap via innovation.

To demonstrate the effect of institutions-as-networks on growth via innovation and imitation, we consider two paradigmatic network structures:

1. Hierarchical networks (a Barabasi-Albert preferential attachment network)
2. Open/flat networks (a Random/small worlds network)

4.1 Hierarchical Networks

[INSERT IMAGE OF PREFERENTIAL ATTACHMENT NETWORK]

The literatures on institutions gives various names to the former type of social arrangement. Acemoglu, Johnson, and

[11] This, in our view, sneaks growth in through the back door.

Robinson (2001) and Acemoglu and Robinson (2012) call these "extractive institutions," Acemoglu (2008) call these "oligarchic societies," and North, Wallis, and Weingast (2009) call these "limited-access orders" or "natural states." A dominant coalition of elites control both political power and economic access and allocate it among themselves in order to extract rents from the rest of the population. Politics and economics are *personal, partial*, and a series of *patronage*-relationships where those without power seek the favor of those with power, in order to gain access to resources and protect themselves from other predatory groups.

We operationalize this institutional setup as a Barabasi-Albert preferential attachment network. The probability that an agent (node) will connect with another agent increases with the number of edges (connections) the other agent has. In patronage terms, one seeks out a patron that has all the right "friends in high places." This relationship forms a power-law distribution, where the overwhelming number of agents have very few connections, and a very small number of agents have a very high number of connections.

There is also significant clustering of agents that form distinct groups in this network, but it is very rare for individuals within a cluster to be connected to individuals outside of the cluster. In most societies throughout history, individuals associate and interact only with other members of their clan or tribe, and seek the patronage of the most powerful members of those groups for access and protection. One can imagine the medieval peasant who in his or her whole life will never step foot outside of their lord's manor, and will intimately know a hundred or so persons, and no more. Members of the elite, aristocratic lords and knights, may interact internationally (via warfare, diplomacy, and foreign missions), but progress and ideas remain stuck within this group. Merchants, to the extent that societies permit them, may interact with other merchants from other societies, and trade information and ideas in addition to goods and services, but again, it is difficult for the formation of new capital and connections to permeate across groups.

A cluster of individuals could be highly productive and very capital-intensive (consider monks in Medieval monasteries) but developments in ethereal (or physical) capital do not spill over to society at large. In fact, ideas and new ethereal capital might be subject to an "echo-chamber" effect, stunting the growth of ideas due to the lack of diverse ideas or experiences that we have seen is necessary to come up with new innovative ideas. Or, the exertion of political power on the cluster of agents deliberately involved in coming up with new ideas (scientists) might distort the ethereal capital structure for political ends: thus the false evolutionary theory of Lysenkoism persisted and was subsidized in the

Soviet Union for decades by Stalin's own personal preference. Scientists that were critical of Lysenko were purged by the State, and the promise of extraordinary advances agricultural productivity never came to fruition, with devastating economic effects.

Ideas are able to "have sex" in this cluster, but it is incestuous.

4.2 Open Networks

[INSERT IMAGE OF SMALL WORLD NETWORK]

The literatures on institutions gives various names to the latter type of social arrangement. Acemoglu, Johnson, and Robinson (2001) and Acemoglu and Robinson (2012) call these "inclusive institutions," Acemoglu (2008) call these "democratic societies," and North, Wallis, and Weingast (2009) call these "open-access orders." There are a plurality of groups that can *compete* for political power and economic resources such that no single group is able to capture the State and extract rents for long (as other groups will form coalitions to oust the abusive group). Politics and economics are *impersonal*, *impartial*, and governed by rule of law that permit nearly anyone (in principle) to acquire economic resources and seek political positions with free entry.

We operationalize this institutional setup as a Random network, where any node will connect to any other node with a random probability. As such, there will be some clusters (groups) that form, but individual members are often connected to other clusters (groups), and are able to capture the benefits of innovations in other groups. As such, productivity-enhancing ethereal capital that spontaneously emerges in one group can be shared and spread to the broader society.

Furthermore, due to the openness of institutions and the omnipresence of political and economic competition, innovators are able to break free of rent-seeking organizations and launch their own enterprises. Thus, the "traitorous eight" that worked for Shockley Semiconductor Laboratory were able to leave and found Fairchild and kickstart the computing revolution in Silicon valley **(CITE)**.

4.3 Connections are Key, and Institutions (Network Rules) Facilitate Connections

We assume that individuals may spontaneously develop useful ideas and that innovation is uniformly distributed across the network (and analogously, uniformly distributed around the world at any point in time). Ridley (2011) argues that

> "Innovation is like a brush fire that burns brightly for a short time, then dies down before flaring up somewhere else. At 50,000 years ago, the hottest hot-spot was west Asia (ovens, bows-and-arrows), at 10,000 the Fertile Crescent (farming, pottery), at 5,000 Mesopotamia (metal, cities), at 2,000 India (textiles, zero), at 1,000 China (porcelain, printing), at 500 Italy (double-entry book-keeping, Leonardo), at 400 the Low Countries (the Amsterdam Exchange Bank), at 300 France (Canal du Midi), at 200 England (steam), at 100 Germany (fertiliser); at 75 America (mass production), at 50 California (credit card), at 25 Japan (Walkman)."

Indeed, we hear stories of young men and women in developing countries that have enormous IQ's, or who make key contributions to mathematics and abstract knowledge, despite being desparately poor and isolated **(CITES)**. Thus, there are probably many equivalents to Einstein and Mozart living in many parts of the world at any point in time, but have no ability to tap into the globalized market for this knowledge to be utilized and generate positive spillovers. Kremer (1993) argues and models how greater population will increase the possibility of innovation, "even if each person's research productivity is independent of population, total research output will increase with population due to the nonrivalry of technology," (684). It further requires integration into global *markets* for people to invest in and exploit productive ethereal capital for economic growth. Romer (1990) points out (with an endogenous growth model) that:

> "If access to a large number of workers or consumers were all that mattered, having a large population would be a good substitute for trade with other nations. The model here suggests that what is important for growth is integration not into an economy with a large number of people but rather into one with a large amount of human capital," (S98).

5 Implications

5.1 "Ideas Before Their Time": Insufficient Network Connections for Complementary Capital

Many inventions, even some seen as the very foundation of modernity and technological advancement, have predecessors harking back decades, sometimes even centuries, to the archaic creations of "inventors ahead of their time."

The Ancient Minoans are widely believed to have the world's first flush toilet circa 2100-1400 BC, well over a thousand years before the Romans Feo et al. (2014, 174). The Ancient Greeks and Romans had "the gear and the screw, the rotary mill and the water-mill, the direct screw-press, glass-blowing and concrete, hollow bronze-casting, the dioptra for surveying, the torsion catapult, the water-clock and water organ, automata (mechanical toys) driven by water and steam," Finley (1965, 29). One of the most mysterious discoveries from the Greek era is the "Antikythera mechanism"[12] which is supposed to be an analogue computer used for predicting astronomical events decades in the future. Hero of Alexandria is said to have invented a steam engine in "aeolipile" in the 1st Century A.D., but it was only put to use opening temple doors. The Ancient Persians (c. 4th Century B.C.) had an ancient refrigerator, the Yakhchal, that allowed them to store food that would quickly spoil, as well as keep ice, despite their desert geography.[13]

One can consider great discoverers and inventors throughout history, from Archimedes to Leonardo da Vinci, who devised ingenious inventions such as airplanes, well before electricity, aluminum, or aerodynamics. Why did none of these lead to economic growth or industrial revolutions until Britain in the 19th century?

> **Proposition 2**: *"ideas before their time" fail because they lack complementary capital goods, which is caused by a lack of network connections, which is determined by the network rules (institutions and attitudes)*

Our framework suggests that the essential problem is that individual nodes in a network that are unconnected to the rest of the network cannot leverage productivity increasing inventions to yield widespread prosperity. Ethereal capital exists only as plans in the minds of individual producers and in the shared institutions (books, libraries, scientific papers, conferences, etc) of a society. A hermit that comes up with a grand idea, even if it were technologically feasible

[12] See https://en.wikipedia.org/wiki/Antikythera_mechanism

[13] See https://www.thevintagenews.com/2017/12/20/yakhchal-ancient-persian-refrigerator/.

(i.e. natural laws permit its existence in the world) and economically viable (i.e. if it were brought to market, consumers would be willing and able to pay more for the product than the sum of the opportunity costs of all of its inputs) is stuck with his or her idea, and no more.

Furthermore, the structure of this network is subject to cultural norms and social attitudes regarding who is worthy of status (and operationally, worthy of connecting to in the network) and what ideas (ethereal capital) are valued and able to be transmitted through the network to be implemented, tweaked, and built upon by successive ideas and commercial ventures.

McCloskey (2007); McCloskey (2011); McCloskey (2016) argues that the fundamental change historically was one of attitudes towards commerce and the social status of merchants and non-elites. Prior to 17th-century Holland and 18-19th century Britain, society looked upon "innovation" as suspect or even seditious, and merchants as unscrupulous swindlers. Baumol (1990) relays many examples of civilizations throughout history where a "well to do" member of the elite would be instructed to make a career in politics, military service, or the bureaucracy. Cicero, Aristotle, and Confucious alike condemned the life of the merchant as unworthy of virtue or social status.[14]

Similarly, Postrel (1998) summarizes the "stasist" point of view, where all radical experiments in the economy and society require permission from authorities. This attitude - which was common for most of human society lived precariously under the Malthusian trap - hampers the incentive to innovate. A famous extreme example, possibly apocryphal, is relayed by Baumol (1990) who quotes Finley (1965, 147):

> There is a story, repeated by a number of Roman writers, that a man - characteristically unnamed - invented un-breakable glass and demonstrated it to Tiberius in anticipation of a great reward. The emperor asked the inventor whether anyone shared his secret and was assured that there was no one else; whereupon his head was promptly removed, lest, said Tiberius, gold be reduced to the value of mud."

In stark contrast, we might consider what Thierer (2016) calls "permissionless innovation" in modern industrialized societies. Only after the revaluation of values in Northwestern Europe in the Modern period are trade and innovation

[14] Ridley (2011, 260) quotes a "Christian missionary in Ming China [who] wrote: 'Any man of genius is paralyzed by the thought that his efforts will bring him punishment rather than rewards."

not only *permitted* as an alternate means of wealth and rising through the ranks, they become encouraged. Rather than waiting for permission from political authorities about whether the "creative destruction" of a new idea would upset tradition or overthrow incumbent rent-extractors, a growing body of scientists, engineers, and merchants (who often wrote to each other, in the "Republic of Letters") radically experimented with and disseminated ideas by their own initiative (Mokyr 1990). None of it was intentional or directed from above, but rather "a semi-directed, groping, bumbling process of trial and error by clever, dexterous professionals with a vague but gradually clearer notion of the processes at work," Mokyr (2003).

Thus, what makes ideas or inventions (and the men and women behind them) "before their time" is precisely the fact that *during* their time, such ideas and inventions were neither valued by society, nor were able to spread through a hierarchical or sparsely-connected network.

5.2 Simultaneous Independent Invention: Complementary Capital Exists with Many Network Connections

> "If I have seen farther than others, it is because I stand on the shoulders of giants." – Isaac Newton

> "It takes a thousand men to invent a telegraph, or a steam engine, or a phonograph, or a photograph, or a telephone or any other important thing—and the last man gets the credit and we forget the others. He added his little mite — that is all he did. These object lessons should teach us that ninety-nine parts of all things that proceed from the intellect are plagiarisms, pure and simple; and the lesson ought to make us modest. But nothing can do that." - Mark Twain[15]

> "Everything of importance has been said before by somebody who did not discover it" – Alfred North Whitehead

History is replete with cases of famous discoveries attributed to one or two great figures, bitter contests between rival claimants to discovery, and famous inventions for which modern researchers uncover multiple silent progenitors.

Gladwell (2008), citing Ogburn and Thomas (1922) describes how,

[15] Letter to Hellen Keller, Perkins Archives, 1903.

> [A] hundred and forty-eight major scientific discoveries [fit] the multiple pattern. Newton and Leibniz both discovered calculus. Charles Darwin and Alfred Russel Wallace both discovered evolution. Three mathematicians "invented" decimal fractions. Oxygen was discovered by Joseph Priestley, in Wiltshire, in 1774, and by Carl Wilhelm Scheele, in Uppsala, a year earlier. Color photography was invented at the same time by Charles Cros and by Louis Ducos du Hauron, in France. Logarithms were invented by John Napier and Henry Briggs in Britain, and by Joost Bürgi in Switzerland.

Merton (1961) points to Francis Bacon's observations that "All innovations, social or scientific, 'are the births of time...rather than wit' " (473). In an ironic twist, Merton's protege, the biologist (and son of Nobel economist George) Stephen (Stigler 1980) coined "Stigler's Law of Eponymy", which states that no scientific discovery is named after its original discoveror, partially tongue-in-cheek to honor Merton's original discovery. Politics and personality may have more to play in the writing of the popular history of inventors and discoverers than the facts.

Additionally, a large number of researchers argue that while a sole inventor with a singular invention often carries the day in popular history (e.g. James Watt and the steam engine, Thomas Edison and electric power, Henry Ford and auto-manufacturing, etc), it requires sequential iterations of second-order inventions over a period of about 20-30 years for the "revolutionary" and "disruptive" invention to reach a critical mass of adoption and impact the economy. Few are bestowed the moniker of "inventor" for inventions that have no practical use or never make it into consumers' homes.

Bessen (2015, 39–40) describes how it usually the second-movers and tinkerers who find a way to improve and practically implement and market the abstract discovery of the first inventor, and that this process takes, on average, 30 years. Rather, commercial success often takes industry standards that allow a thick market for skilled labor to develop, which in turn boosts wages through intra-industry firm competition, encouraging more workers to invest in human capital. Such standards require several decades to emerge. Important industries appear to take about 29 years on average from the "original invention" to its widespread commercial adoption (p.39). Bessen (2015, 67ff) also puts forth a theory of several stages of innovation diffusion and its impacts on market structure (c.f. Gort and Klepper (1982), Klepper (1996), Auerswald et al. (2000)). Following the 3 decades it takes for an innovation to reach commercialization, over another 3 decades there is a "shakeout" where many incumbent firms go bankrupt, exit, or merge in an increasingly concentrated and declining industry.

The true "discoverer" or "inventor" of the automobile, if there truly ever was just one person, is lost to history. Henry Ford, however, is the one who is widely celebrated in association with the automobile; but in Ford's own words, he "simply assembled into a car the discoveries of other men behind whom were centuries of work," (Ridley 2011). It was Newton after all, the famous "discoverer" of gravity, who modestly claimed that if he had seen farther than others, it was by standing on the shoulders of giants.

Our framework helps explain this curious phenomena of simultaneous invention, and also of the need for the "inventor" (or inventors, plural) and her invention to be improved upon and tweaked by others before it leads to commercial success, and inventions in the aggregate compound into economic growth. Both physical and ethereal capital structures must contain the complementary goods necessary for a sole genius' invention to be both technologically feasible and economically profitable. Da Vinci's flying machines failed to take off because they lacked both the concept of aerodynamics and the modern resources of aluminum, not to mention an institutional framework where such radical notions were celebrated and improved upon. Otherwise, we can view, as their contemporaries did, the inventions of people inventing in the wrong time as bizarre outliers due to an inconsistent capital structure. To talk about computers in Ancient Greece or the movement of Earth around the Sun would seem strange and even heretical to academics and laypeople alike who have no complementary knowledge (an complementary physical capital) backing that up.

> **Proposition 3**: *when there are existing physical and ethereeal capital goods that complement an idea, and there are many network connections, an invention is "ripe" to be invented by multiple persons in the network.*

Likewise, we can understand the phenomenon of simultaneous independent discoveries or close competition over first-discovery-calculus between Newton and Leibniz; marginalism between Menger, Walrus, and Jevons; the airplane between the Wright Brothers and the Smithsonian. The time was "ripe" for someone to discover these ideas because the complementary intellectual and physical capital structures had been in place: if Newton did not discover calculus, Leibniz would have, if not Leibniz, someone else was bound to, given the tools and the puzzles of mathematics at the time. If Alexander Graham Bell had not "invented" the telephone, Elisha Gray would have (and Bell infamously beat Gray to the patent office by a few hours), (Gladwell 2008).

Thomas Edison couldn't just spark the electrification of America by "inventing the lightbulb." He needed the resources provided by countless materials available for testing, a scientific method of experimentation, patents and a culture that rewards innovation, an advanced financial system to fund a power plant necessary to generate electricity for the lights, methods of manufacturing mass production, and so much more. All of these ingredients prevented him from suffering the fate of the apocryphal glassmaker in Imperial Rome. Furthermore, David (1990) memorably describes how it took about 30 years from Edison's famous test in Manhattan in 1890, for half of Americans to have electricity power their homes or managers to update their factories from steam to electic power. It was all of the *second-order* innovations and improvements that integrated electricity into a new format of factory that would ultimately enhance productivity.

5.3 The Failure of Modern Technology Transfers for Development

One proposal for assisting developing countries is for developed countries to technology transfer: organizations (firms, trade associations, universities, governments, NGOs, etc) in wealthy and advanced economies simply transfer technology to those in poor and developing economies.

The problem lies in assuming that the missing link is simply technical knowhow or even physical machines. On the technical economic merits, ideas appear to be the purest form of nonrival public good: once a discover finds a chemical formula or builds a better moustrap, others can use the same idea (if not the same *physical* equipment, which *is* rivalrous) without diminishing another's ability to use it.[16] However ideas are quite costly to replicate. Mansfield, Schwartz, and Wagner (1981) estimates that across 48 different products that were reverse engineered and copied by market competitors that the cost to those competitors of copying constituted about 65% of the cost of the original innovation and 70% of the time it took the first-mover to come to market. Kealey and Ricketts (2014) generalize this to argue that discoveries and research are not pure public goods, since their "spillover effects" are only accessible to those with the requisite tacit knowledge and training in the disciplines.

Bessen (2015) relates that,

[16]They may, however, diminish the discoverer's profits. Most countries have made the utilitarian tradeoff to incentivize creation by granting temporary monopolies to first publishers in the form of intellectual property rights laws.

> By the early twentieth century, British textile equipment manufacturers were shipping power looms and other textile equipment around the globe. Mills in India, China, and elsewhere not only used the same equipment as British mills, but they were often run by experienced British managers aided by British master weavers and spinners and engineers. Nevertheless, their output per worker was far less than that of the English or American mills because their workers – using the exact same machines – lacked the same knowledge and skills. Western weavers were 6.5 times more productive. The English and American cotton textile industries held a sustained economic advantage for decades, despite paying much higher wages. (pp.18-19)

Thus, merely transferring of knowledge - even when packaged with expert workers, managers, and complementary (physical) capital goods - is often insufficient to promote economic growth in target countries.

Our framework explains this failure by pointing to the differences in network structure (rules and connections) and how taking a high-productivity idea or machine (ethereal or physical capital) out of one network and placing it into another will not generate higher productivity and output per capita.

> **Proposition 4**: *physical and ethereal capital generated in one network configuration cannot easily be transplanted into another network with different a configuration (institutions).*

This echoes the claims made by Bauer (2000) about flawed views among development economists about the feasibility of foreign aid or technology gransfer programs. Technology that originates in the first world emerges in the context of a large division of labor and highly capital-intensive structure of production and specialization.

Bauer (2000) shows that in many developing countries, large-scale production, even if technologically efficient, is economically inefficient. Adam Smith's dictum that "the division of labor is limited by the extent of the market" implies that with underdeveloped markets, large-scale production is uneconomical. Construction firms in wealthy nations do not dig ditches with shovels, but with bulldozers and excavators. In many developing countries, workers dig ditches with shovels or cruder tools. Simply giving a farmer or an engineer in that Third World country an excavator and teaching them how to use it is insufficient. Certainly with a reasonably limited amount of training, any person from any country can successfully learn how to operate a tractor. But if the farmer is only digging the ditch to grow a crop that he can sell to 25 people, the tractor makes no sense at that scale. In fact, the purchase of an excavator will increase his average costs; even if he is gifted it through a foreign aid program, it will still incur costs from storage, fuel purchases, maintenance, depreciation, and so on. In the First World, we might expect such a purchase to lower the average cost by increasing productivity, but only because our division of labor is so large that we can amortize this large cost by producing and selling at such an enormous volume. Were that African farmer to sell his crops to million of consumers across the world, such a tractor would probably make financial sense. As Smith noted, our specializations and talents are far less inherent than we think, and are not the cause but rather the effect of a large division of labor. The Third World farmer is not inherently stupid or lazy, the division of labor is limited by a small market, which restricts specialization and capital accumulation. There are no already-existing complementary capital goods (fuel, machine tools, storage facilities, etc) that allow the excavator to fit into the production plan.

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