THE STANDARDIZATION OF STANDARDIZATION: THE SEARCH FOR ORDER IN COMPLEX SYSTEMS

by

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A Dissertation
Submitted to the
Graduate Faculty
of
George Mason University
in Partial Fulfillment of
The Requirements for the Degree
of
Doctor of Philosophy
Public Policy

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DEDICATION

This is dedicated to my loving wife Andrea, who has supported me through this long process, and to my three children, Ewan, Paul, and Thea who inspired me to go study.

ACKNOWLEDGEMENTS

I would like to thank the many friends, relatives, and supporters who have made this happen. My advisers deserve a special notice of thanks. I had the good fortune to take two classes with Dr. Auerswald. Over the years he has been an inspiring force in my career and has consistently motivated me to get words on the page. I was also fortunate to have two classes with Dr. Root. His courses provided a new lens to see the world, while also providing expert knowledge of Europe and East Asia and the comparison between them. I owe a tremendous debt of gratitude to Dr. Hart, who has graciously agreed to help in each stage of my studies. Dr. Hart's knowledge of science and technology policy has been invaluable as I worked through the role of standards in our system.

I was fortunate to have understanding colleagues at my work. I would not have been able to finish the dissertation without the tacit approval of Dr. Foster. He has been a helpful resource as well as an empathetic supervisor. Dr. Bird offered support along the way and was kind enough to read my work at early stages and offered helpful suggestions.

The George Mason campus, and the Schar School of Policy and Government in particular, has been a supportive space to work. The Ph.D. workshops at the Schar School have been a collegial environment in which to present my work over the years and I am grateful to the faculty and the students who offered constructive feedback.

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LIST OF ABBREVIATIONS AND SYMBOLS

American National Standards Institute	ANSI
American Engineering Standards Committee	AESC
American Institute of Electrical Engineers	IEEE
American Society of Mechanical Engineers	ASME
American Society of Safety Engineers	ASSE
American Society of Testing and Materials	ASTM
American Standards Association	ASA
The British Standards Institution	BSI
Complex Adaptive Systems	CAS
Defense Advanced Research Projects Agency	DARPA
Euro	€
General Agreement on Tariffs and Trade	GATT
Global Supply Chain	GSC
Information and Communications Technology	ICT
International Federation of the National Standardizing Associations	IFA
International Electrotechnical Commission	IEC
International Federation of the National Standardizing Associations	ISA
International Organization for Standardization	ISO
International System of Units	SI
International Telecommunication Union	ITU
National Bureau of Standards	NBS
National Institute of Science and Technology	NIST
Office of Technology Assessment, U.S. Congress	OTA
Open Systems Interconnection	OSI
Quality Management System	QMS
Science and Technology Studies	STS
Standard-setting Organization	SSO
Supply Chain Management	SCM
United Kingdom	UK
United Nations Standards Coordinating Committee	UNSCC
United States of America Standards Institute	USASI
World Trade Organization	WTO

ABSTRACT

THE STANDARDIZATION OF STANDARDIZATION: THE SEARCH FOR ORDER IN COMPLEX SYSTEMS

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This dissertation examines the patterns of institutional change associated with globalization from the perspective of standard-setting institutions: Has globalization resulted in convergence or divergence of the institutional structure of standard-setting processes? Furthermore, what forces or conditions of the globalization experience have accounted for observed episodes of convergence or divergence and how have the institutional structures of standard-setting responded to the pressures of globalization since the late 19th century?

I find that the evolution of standard-setting institutions has manifested patterns of both convergence and divergence over the past 150 years, and that the variations observed can be linked to differences in the pace and nature of the underlying globalization experienced at different times and in different places. I find that swings between patterns of institutional convergence and institutional divergence reflect the

reality that globalization itself is not a homogeneous historical process. Rather it has been composed of different and sometimes conflicting strands of changing social, political and economic conditions and relationships. By identifying the relationship between certain patterns of globalization and those associated with the development of standard-setting institutions, this study provides analytical tools based on concepts from complexity theory that may be useful for understanding the possible future development of these institutions.

INTRODUCTION

Global integration has been reflected in the evolution of social, political, legal and economic institutions in diverse ways. This dissertation examines the patterns of institutional change associated with globalization, from the perspective of standard-setting institutions. The primary research questions are concerned with the relationship between standard-setting organizations and the ongoing process of globalization. Specifically, has globalization resulted in convergence or divergence of the institutional structure of standard-setting processes? Furthermore, what forces or conditions of the globalization experience have accounted for observed episodes of convergence or divergence and how have the institutional structures of standard-setting responded to the pressures of globalization since the late 19th century?

The term convergence is used in two forms throughout the dissertation.[1] First, convergence refers to the creation of institutions for standard-setting across countries or across industries. Almost all countries have created a standard-setting organization at the national level to manage the domestic process of standardization and to serve as a liaison to international standard-setting organizations, such as the International Organization for

[1] The concept of convergence has also been applied to the study of the convergence of global income and to the convergence of political institutions and forms of government.

Standardization (ISO).[2] Second, convergence is synonymous with harmonization of specific standards across countries. A standard can be adopted globally through various mechanisms, but it has been common for ISO to coordinate the global process of standard-setting.

Divergence, on the other hand, refers to the variation among the same variables and institutions. For example, there is considerable variation in how standard-setting activities are conducted across countries. In most Western economies, there is greater reliance on voluntary consensus standards than in East Asia, where the process in more centralized (Tate 2001). Divergence may also describe the fragmentation in the standard-setting process that has occurred during the past 30 years, and at other times through history. Recently, standard-setting activity in the information and communication technology (ICT) sector has undergone rapid change and standards are no longer predominantly created through international organizations (the highest level in the standard-setting system), but are instead created through new industry consortia, a development that will be discussed in greater detail in chapter 5.

The study of standard-setting organizations is important because they have been essential to the foundation of modern trade, to the creation of new platform economies based on firm-level standards for matching, and have been an important ordering mechanism during tumultuous periods of globalization.

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[2] According to ISO, "Because 'International Organization for Standardization' would have different acronyms in different languages (IOS in English, OIN in French for *Organisation internationale de normalisation*), our founders decided to give it the short form ISO. ISO is derived from the Greek isos, meaning equal. Whatever the country, whatever the language, we are always ISO." From https://www.iso.org/about-us.html (Accessed June 24, 2017).

Standard-setting organizations are one type of formal institution. There has been considerable interest in what these institutions contribute to variables of interest, such as economic output or development, particularly because standardization activities have spread to most countries in the world, a theme discussed in Chapter 4. Douglas North (1991, 97) defines institutions as the “humanly devised constraints that structure political, economic and social interaction. They consist of both informal constraints (sanctions, taboos, customs, traditions, and codes of conduct), and formal rules (constitutions, laws, property rights).” The principle way institutions matter is in shaping the incentives of individual agents.

Standard-setting organizations are one type of institution that has been transplanted into nearly every country in the world. By studying the diffusion of standard-setting organizations, this dissertation aims to improve understanding of institutional convergence.

I find that the evolution of standard-setting institutions has manifested patterns of both convergence and divergence over the past 150 years, and that the variations observed can be linked to differences in the pace and nature of the underlying globalization experienced at different times and in different places. I find that swings between patterns of institutional convergence and institutional divergence reflect the reality that globalization itself is not a homogeneous historical process. Rather it has been composed of different and sometimes conflicting strands of changing social, political and economic conditions and relationships. By identifying the relationship between certain patterns of globalization and those associated with the development of standard-setting institutions, this study provides analytical tools that may be useful for understanding the possible future development of these institutions.

Globalization as Standardization

Standardization is a process that occupied some of the earliest human civilizations (such as the Sumerians) as they attempted to generate order out of a harsh environment.[3] Early standardization efforts included establishing methods of keeping time, early calendars based on the movement of the sun, moon, and stars to better time agricultural harvests, and various measurement standards (ANSI 2014b). Initial ad hoc attempts eventually transitioned to standardization by royal decree and through administrative directive.

Standardization became increasingly important as city-states developed large-scale administrative capabilities. Standardization activities have historically coincided with trade and bureaucratic expansion. As the Roman Empire spread over geographic space, it brought standardized roads, education systems, and methods of governance. Likewise, the first emperor of China, Qin Shi Huangdi (221 BCE to 206 BCE), standardized both writing and weights and measures, with the aim of increasing trade within the newly unified country. Similarly, King Henry I introduced formal standards in England (also to facilitate commerce) when he created the *ell*, a measure based on the length of his forearm (ANSI 2014b).

Standards have enabled global commerce throughout history, but became especially critical during the second industrial revolution. The second industrial

[3] For an accessible and entertaining history of measurement standards through history see (Hebra 2003).

revolution was a special time when it comes to standards because it marked the first time private consensus standards were developed. New industry associations emerged during this period as a response to increasing trade flows and to the rapid pace of technological change through industrialization. Standards were created to solve particular needs, such as developing standardized testing methods to ensure the quality and reliability of new goods. New institutions managed the process of standard-setting and promulgated standards beyond their home country. For example, standards created by the Association of Testing and Materials (ASTM), an American institution, were adopted globally. These new institutions helped spread a new language that could be shared and relied upon to coordinate activities between countries.

In that sense, a core conjecture of this dissertation is that standards epitomize the process of globalization, and standardization at its core involves bringing order and consistency to transactions. Although Sen (2002) describes globalization as a centuries-long process, the specific focus on globalization over the past 150 years coincides with the rise and spread of standard-setting activities through increasingly dense networks of production (Agwara, Auerswald, and Higginbotham 2015).

The second industrial revolution was an important period when it comes to standards, but it was also an important time when it comes to industrialization and globalization. There have been two major periods of globalization, as measured by global trade flows, since the mid-19th century (Baldwin and Martin 1999). The first began in the mid-19th century and ended with the onset of World War I (what is now referred to as the second industrial revolution).

After an interlude between the two world wars that included the Great Depression, the second era of globalization began during the reconstruction after World War II. Standardization activity coalesced around a system of global standard-setting organizations after WWII and this process of standard-setting has been an important factor in the increase of global trade in the ensuing period. It is for this reason that my colleagues and I concluded that globalization and standardization are inextricably intertwined (see Agwara, Auerswald, and Higginbotham 2015).

An Introduction to Standards

A reasonable starting point for the modern system of standards and standardization is with government control of weights, measures, and monetary standards written into constitutions (Spring 2016, 34). In the United States, Article 1, Section 8 of the U.S. Constitution authorizes the federal government to "fix the standard of weights and measures" and "to coin money." Congress quickly and repeatedly shaped currency policy, but formal metrology standards for weights and measures were not introduced until the 20th century with the creation of the National Bureau of Standards, the predecessor of NIST (Cochrane 1966, 24).[4] However, considerable private standard-setting activity had begun in the late 19th century.

One of the ironies about standardization, as Andrew Russell (2008, 3) notes, is the lack of definitions, such as what standards are, what they do, and how they are created

[4] The U.S. did adopt the decimal system in short order. In addition there was a small office as part of the Treasury's Coast Survey, dating from the mid-1830s, but little other activity. There were reports and statements of support from American leaders (President Washington, Secretary of State Thomas Jefferson, President James Madison, and Secretary of State John Quincy Adams) urging the establishment of uniform standards in weights and measures but no subsequent action (Cochrane 1966, 21)

and agreed upon.[5] A starting point is to separate the defining elements of a standard, or the actual function of a standard, from the net impact, or outcome of the standard (Swann 2010, 12).

It is also helpful to specify why standards are being studied. There are many different types of standards across different markets. What we emphasize, and how we define concepts and select cases, influences the answers we receive (B. Geddes 1990). As a result, definitions of standards may be domain specific and emphasize some elements of standardization that other fields or authors do not.

At the risk of oversimplification, and understanding there is some overlap across disciplines, one simple categorization is that economists seek to understand how standards are set in the market, and under what conditions, how incentives are created and maintained, and the costs and benefits of standards (see for example Blind 2004; David and Greenstein 1990; David and Steinmueller 1994; Swann 2010). Political scientists have examined how power relationships within governance structures affect which parties are able to shape standard-setting activities to reflect their priorities (Buthe and Mattli 2013; Drezner 2007; Mattli and Büthe 2003). Sociologists have examined how social norms affect and shape individual action and how standard-setting organizations create a system of rationalization (Bromley and Meyer 2015; Busch 2011; Mendel 2001). Government actors (bureaucrats) associate standards with regulations to address health and safety concerns or achieve a social end (OTA 1992, 5). Private actors such as

[5] Russell's research question focused on ICT and therefore adopted the definition from David and Greenstein (1990, 4) who defined standards as: "a set of technical specifications adhered to by a producer, either tacitly or as a result of a formal agreement." This is a particularly good definition for questions relating to the ICT industry, but too narrow for the present research approach.

engineers, by contrast, may see the standard-setting process as technocratic and a domain for experts (Agnew 1926).

The emphasis of this dissertation will be the role standards play in creating order. The establishment and maintenance of ordered systems is a primary goal of ISO, as emphasized in its definition of a standard as a “document, established by consensus and approved by a recognized body, that provides, for common and repeated use, rules, guidelines or characteristics for activities or their results, aimed at the achievement of the optimum degree of order in a given context” (ISO 2004). Furthermore, ISO includes a clarifying note below the definition, which states: “Standards should be based on the consolidated results of science, technology and experience, and aimed at the promotion of optimum community benefits.”

Having adopted a working definition for standardization, it is now important to enumerate the different types of standards produced, how they are produced, and by whom.

Types of Standards

There are several different categorization methods for standards. For example, ISO defines three categories. “Standards can be broadly sub-divided into three categories, namely product, process and management system standards. The first refers to characteristics related to quality and safety for example. Process standards refer to the conditions under which products and services are to be produced, packaged or refined. Management system standards assist organizations to manage their operations. They are often used to help create a framework that then allows the organization to consistently achieve the requirements that are set out in product and process standards" (ISO 2012a). The OTA's definition included product and process standards, but rather than management standards included control standards. These, according to OTA, are designed to address a societal hazard or problem and generally define a range of acceptable performance, or use of a project (OTA 1992, 100). Paul David (1987) classifies standards based on their economic function.

A common approach is to classify standards in one of four categories: reference, compatibility, interchangeability, and quality standards, with some room for overlap (Blind 2004; David and Greenstein 1990; Guasch et al 2007.) One common characteristic intrinsic to all standards is that they codify technological knowledge (Blind and Jungmittag 2008). This is an important point meriting additional explication.

Reference standards (information or measurement standards) tie the value of one object to a reference base (NIST/SEMATECH 2012). Standardized weights and measures are a typical example of these standards. A weight measurement serves as a metaphor or simile. For example, a standardized pound on a scale is used to measure a comparable weight of another object, such as a bag of oranges (Busch 2011, 10).

Compatibility (interface) standards enable different components of a system to work together because they are based on common characteristics (David and Greenstein 1990). The railroads, one of the first network industries, are a clear example because commercial and passenger rail both work on the same tracks (Blind 2004).

Interchangeability standards refer to parts that are interchangeable and for the most part identical. The industrial revolution and the rise of assembly line processes at the beginning of the 20th century required that tools in engineering be standardized (Brady 1961). As a result, standardized components from one manufacturer can be expected to work just as well as another. This is not limited to engineering but extends to many practical products, such as paper products (Guasch et al. 2007; Blind 2004.)

Quality and safety standards certify to consumers that a product or service was produced in a specific manner with a consistent minimum allowable quality. The best known process standards are the ISO quality management standards.[6] These standards are discussed extensively in chapter 5. On the product side, health and safety standards for toys, food, drugs and electrical appliances fall into this category and are all subject to minimum quality standards (Guasch et al. 2007.)

The types of standards described above are all relate to market activities, but standards do not have to be market oriented. Standardization is analogous to the establishment of social norms in society aimed at improving daily life by simplifying some decisions. For example, when we drive on the right or the left side of the road, we do so primarily for local historical reasons and not because one design is clearly superior or provides a higher market return. People simply have to coordinate on one set of standards or norms to reduce the confusion that would otherwise arise, or that previously

[6] The two most common ISO management standards are the ISO 9000 and 14000 series. ISO 9000 addresses "Quality Management." This covers what an organization does to fulfill quality and regulatory requirements, enhance customer satisfaction, and achieve continual performance improvement. ISO 9000 consists of internationally agreed principles and requirements for managing an enterprise so as to earn the confidence of customers and markets (Brunsson and Jacobsson 2002, 71). ISO 14000 addresses environmental management. These standards cover what an organization does to minimize harmful effects on the environment caused by its activities and what it does to achieve continual improvement of its environmental performance.

occurred. Standards making, in this context, is a process of social ordering and of making the world more rational (Drori, Meyer, and Hwang 2006; Karabasz 1928).

The Formal Status of Standards

Standards are classified based on their type and also on their formal status. Informal or *de facto* standards are norms or requirements that may be voluntarily adopted and that frequently arise as a result of path dependence and emergence.[7] There are two types of *de facto* standards, those adopted by the market through some type of competition mechanism, and standards that are negotiated on a voluntary consensus basis. Formal, or *de jure*, standards have the force of law behind them, either as laws, regulations, or contracts (Rycroft and Kash 1999). These are flexible categories and there may be some movement between types over time. For example, voluntary consensus standards may be referenced in government procurement or regulation and therefore take on de jure status. In modern trade agreements countries are instructed to use the most widely agreed upon international standards when possible.

Who Creates Standards?

The standards ecosystem is composed of a diverse set of organizations. Today there exist hundreds of organizations involved in setting voluntary consensus standards. Cheit (1990, 23) specifies four types of private standard-setting organizations: (1) trade associations; (2) professional societies; (3) general membership organizations; and (4) third party certifiers. To this list it is important to add industry consortia, which emerged alongside the development of the ICT sector (Updegrove 2017).

[7] Path dependence implies that current decisions are influenced by previous actions and decisions.

Trade associations represent their membership base and promote standards that benefit their membership.[8] The American Petroleum Institute (API) has produced standards for its industry since 1924. Trade associations typically have membership dues, and therefore may not charge for standards, and in most cases they do not rely on standards as their primary source of funding.

Professional societies represent some of the oldest standard-setting organizations in existence. The American Society of Mechanical Engineers (ASME), for example, was founded in 1880. These societies' memberships are composed of specific types of professionals, such as electrical or mechanical engineers. They frequently sell their standards to their members, which may be an important source of ongoing revenue.

General membership organizations are the broadest type, representing an extensive swath of the market. Founded in 1898, the Association of Testing and Materials (ASTM) has issued more than 12,000 standards across industries and product types, including plastics, cement, and steel. More recently, it has issued standards on health care and services.

Independent consortia are comparably new standard-setting organizations that were developed to create standards for the fast-moving ICT industries. They will be discussed in more detail in chapter 5.

Finally, certification bodies like the Underwriters Laboratories provide independent testing to confirm products meet certain standards and specifications.

[8] Not all trade associations issue standards.

Farrell and Saloner (1988) compare standard-setting in committees with market-based standardization processes in which a leader sets a standard and others follow (a bandwagon model). They found the committee structure is more likely to achieve coordination, despite being slower. They do find that a hybrid committee structure with a lead-firm that coordinates standard-setting activities can perform even better.

The Central Role of Institutions

The link between standards and globalization has been through institutions. Since the first standard-setting organizations were created in the 19th century there has been a continual though sometimes disjointed process of convergence to global governance of the standardization ecosystem. This process culminated in the post-WWII years with the creation of the International Organization for Standardization (ISO) in 1946. ISO complemented two existing international standards organizations, the International Electrotechnical Commission (IEC) and International Telecommunication Union (ITU). Together these three organizations were able to coordinate the efforts of their member countries and to help build the modern trading system by providing a venue for the creation of an agreement on international standards, which are the backbone of the international trading system.

However, this convergence toward standardization at the global level did not create a homogenous system. In fact, there is considerable variation in how nations promulgate and diffuse standards at the level of nation-states, which is a common feature of complex systems.

It is common to see stability and similarity at the higher levels of a system while experiencing increased diversity and variation at the micro level (Root 2013, 8; H. A. Simon 1996).

Hierarchy is a common characteristic of technological systems. The study of institutions as part of a system of components, all interacting and co-evolving, can lead to the study of one subsystem or level of analysis. In a large technological system, there is a risk that isolating one component, or institution, may provide only a partial analysis of system behavior (Hughes 1987, 55).

The independent standard-setting institutions function as components of a system and interact with other institutions, all of which contribute directly or indirectly to the common system goal (Hughes 1987, 51). If an institution is removed from the system, or if its characteristics change, the other institutions in the system will also change (Hanseth et al. 2006).

At the micro level, the relevant unit of analysis is an individual firm or an association composed of the affected firms and individuals.[9] The scale in standardization policy runs from the individual firm to global standard-setting institutions. There is considerable variation between countries in the relationship and the role of local standard-setting entities and the national government, which makes the level of the state particularly interesting.

[9] Cheit specifies four types of organizations at this level: (1) trade associations; (2) professional societies; (3) General membership organizations; (4) third party certifiers (Cheit 1990, 23). Certification is an important activity but is distinct from the process of creating standards and will not be discussed in the dissertation, except in respect to ISO certifications.

The process of setting standards is organized in a variety of ways across countries. The United States was one of a small group of advanced industrial states that created a formal standard-setting system at the start of the 20th century. The United Kingdom (1901) and the Netherlands (1916) created standardization organizations at the national level before or during WWI, but the first sustained burst of activity at the national level occurred during the period of peace between the two world wars.

The American system of voluntary consensus standardization is loosely coordinated by the American National Standards Institute (ANSI).[10] The American system of voluntary consensus-setting that has gradually emerged faced conditions at its inception that differed considerably from the environment in continental Europe and the U.K., and it therefore embodies the idiosyncrasies of 19th-century America.

The U.S. system of standardization, like many of its economic systems and institutions, is largely a bottom-up creation in which ideas that percolate within firms may advance to higher levels in the system. The process is often reversed in Europe, which has what may be considered a top-down system.[11] There are exceptions to this generality: during the two world wars, the U.S. government assumed an active role in shifting the focus from standardization to the consolidation of the quantity and variety of standards, and to ensuring safety through regulatory standards, such as building and fire

[10] I use ANSI throughout the dissertation to avoid confusion, but the organization has changed names repeatedly through history. At its creation it was named the American Engineering Standards Committee. It was enlarged and renamed in 1928 as the American Standards Association (ASA.) This lasted until 1966 when ASA was reorganized and renamed again as the United States of America Standards Institute (USASI). This change was short lived and in 1969 was changed to the American National Standards Institute (ANSI), which is its current name.

[11] This is a broad generalization. Social systems are rarely purely binary in nature. In the U.S. some standards are proposed at the highest levels and then receive feedback from firms and indviduals. Likewise, micro level actors often influence European policymakers.

codes (Office of Technology Assessment (OTA) 1992; Ranville 2014). In general, however, the U.S. pursues a more distributed method for producing standards.

The framework for U.S. standardization policy has shifted over time. There was considerable debate about the appropriate role of the government in standard-setting activities during the late 19th century. Despite initial interest in standard-setting in the nascent republic, the National Institute for Standards and Technology (NIST) was not founded until 1901.[12] ANSI was formed with three government agencies alongside five standard-setting organizations in 1918. Herbert Hoover, as Commerce Secretary, was a respected advocate for the "associative state" in which standard-setting would play a fundamental role. However, it was not until the mid-20th century that government, particularly through the Department of Defense, played a central role in the innovation process (Bonvillian 2009; Hart 2010, see chap. 8). New issues and concerns have emerged in recent years. NIST, which used to focus on traditional standardization activities like establishing reference weights and measures, now finds itself coordinating efforts in high-tech sectors on issues like cyber security and the smart grid.

What are the effects of this decentralized approach? At times it has been criticized for making U.S. firms and industries less competitive in global markets (OTA 1992) but ANSI, by contrast, extolls the current system and sees the need for only minor improvements (ANSI 2015). In reality, the U.S. standards system is complex; it has sometimes been successful and has sometimes been an impediment to innovation.

[12] NIST's name has evolved over the years, starting in 1901 when it was named the National Bureau of Standards. In 1903 the word "national" was removed only to be added again in 1934. The organization took its current name in 1988.

Research by political scientists has demonstrated that U.S. firms and interests are better represented in certain global forums and in certain types of standard-setting activities than in institutions like ISO, where power is more concentrated by European participants (Buthe and Mattli 2013; Mattli and Büthe 2003).

The Process of Standard-Setting

Institutions at the national level may cooperate with higher levels in the system, but they do not have to—cooperation of activity at the highest level is not inevitable. The early predecessor of ISO—the International Federation of the National Standardizing Associations, or IFA—fared about as well as the League of Nations. IFA failed in part because it was underfunded and lacked agreement on its priorities, but also because the participants could not agree to a common set of measurement standards (Latimer 1997). When the member countries convened after WWII to create ISO, they agreed to forego any discussions of the International System (SI) and abdicated those decisions to the member states.

Fragmentation

One central theme of this dissertation is that the standards ecosystem has experienced periods of convergence and global harmonization, but also of fragmentation and divergence. The process of standardization stabilized after the creation of ISO, but it was not long before the system experienced another shock. The information and communications technology (ICT) revolution had a profound impact on this system. Not only were the established processes at existing standard-setting organizations perceived to be too slow, but ICT firms also created new processes for developing standards. This had a lasting impact on the future trajectory of the standard-setting organizations.

To meet the demands of the new era in networked communication, firms increasingly turned toward private consortia to address their needs (Cargill 1996; Egyedi 2014; Updegrove 2017). The nature of ICT also brought the additional complication of property rights. Most, if not all, ICT standards cite patents and licensing these patents has become a contentious topic. Standards organizations require that essential patents—those required for the standard—be licensed on equitable terms, known as Fair, Reasonable, and Non Discriminatory Licensing. There is concern that the U.S. system in particular, which defers considerable decision-making authority to private organizations, is not well equipped to address these licensing issues (Lerner and Tirole 2015).

To understand the recent structural changes in the system and the demands on the modern U.S. standard-setting process requires first considering the evolution of standards within the U.S. economy and the institutional arrangements that have promoted their development (OTA 1992, 39). A comparative framework allows for a better understanding about what makes the U.S. system unique and also provides insight about the future trajectory of other standard-setting organizations across the different levels of the global system.

To understand the variation in periods of convergence and divergence requires understanding three related factors: (1) the state, and rate of change, of underlying technology, (2) shifts in costs, and (3) benefits of harmonizing standards through global institutions. While it might seem obvious that standards should be agreed upon at the international level, there are important differences in how these organizations are designed and how they operate, which affects the demand for their services.

Organization of the Dissertation

This dissertation is about the process of standard-setting and the global governance that has emerged to manage the set of standard-setting institutions. The methodological approach incorporates research from economic history, institutional theory and public policy analysis.[13] The structure of the dissertation is as follows.

Chapter 2 examines the costs and benefits inherit in standard-setting activities. Duplicative standard-setting by multiple countries, or industry associations between countries, can create compatibility problems and may favor some firms in international trade at the expense of others. There is a general consensus, codified by the World Trade Organization, that standards should be agreed upon through international organizations whenever possible. Chapter 2 also introduces the question of how changes in technology affect the institutional structure of standardization. Following the discussion of standards is a section on the new fields of complexity and evolutionary economics. I provide a discussion about how complexity theory may be able to better inform our understanding of standardization activities. This framework will be applied in subsequent research questions.

[13] One problem with the study of standardization is that it lacks even basic descriptive statistics. Thus, we do not know how many standards there are in a particular industry or country, which firms are the dominant sponsors, and who actively participates in standard-setting activities. The study of patents has advanced relative to research on standards in part because of the database created by Adam Jaffe and colleagues. There is no comparable data set about standards, although there is a small cohort of scholars at Northwestern University working to address this problem (see Baron and Spulber 2015).

Chapter 3 analyzes the rise of standard-setting organizations in the second industrial revolution and asks why these organizations were formed at this particular point in history. Specifically, the chapter examines what characteristics of the second industrial revolution, such as the observed increase in global trade flows and the rapid acceleration of the processes of industrialization, contributed to the formation of new standard-setting institutions.

Chapter 4 chronicles the transition from industry and firm-based standardization activities to national standard-setting systems. The chapter analyzes the role of standard-setting organizations throughout three distinct time periods: (1) from the founding of the first national standard-setting organization in Great Britain until the onset of WWII; (2) during the period following WWII until the mid-1980s; and (3) in the third industrial revolution, which started around 1990.

Chapter 5 chronicles the creation of the International Organization of Standardization (ISO). The global economy was building toward a period of increased interdependence with denser trading networks. ISO facilitated this process by harmonizing product standards, however the revolution in information and communications technology created a systemic shock that altered ISO's development. This led to a period of fragmentation that is still ongoing, despite the broader trend towards more tightly integrated global networks of production. The chapter examines how ISO responded, analyzes the impact on other levels of the system, and seeks to understand how the interconnected nature of the standard-setting system created new opportunities while also creating new challenges for incumbents.

Chapter 6 concludes the dissertation by tying together the different time periods and themes. Furthermore, the chapter analyzes whether the narrative history around standardization, and the specific cases presented in the dissertation, can be better understood through the application of theoretical tools from evolutionary economics and complexity theory. These new theories provide an alternative lens to view the study of change processes and it is important to understand if they provide greater explanatory power relative to conventional approaches.

THE TENSION BETWEEN ORDER AND FLEXIBILITY IN STANDARDIZATION

The research questions of this dissertation relate to the patterns of institutional change associated with globalization from the perspective of standard-setting institutions: Has increased economic integration and interdependence resulted in convergence or divergence of the institutional structure of standards and standard-setting processes? Furthermore, what forces or conditions of the globalization experience have accounted for observed episodes of convergence or divergence and how have the institutional structures of standard-setting responded to the pressures of globalization since the late 19th century?

Over the past 40 years economists have gradually incorporated important features of evolutionary biology into economic analysis, a research program inspired by Schumpeter's seminal writing (Nelson and Winter 1982). Economists seeking to explain dynamic rather than static problems have gradually adopted an evolutionary framework (Metcalfe 1994, 1995; Nelson and Winter 1982). [14]

Since the introduction of evolutionary ideas into social sciences, a broader discipline (complexity theory) has partially subsumed evolutionary theory by incorporating ecological perspectives. The significance of these changes is evident in

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[14] Although Schumpeter used the terms "dynamic" and "static" frequently, he found it preferable to avoid these terms when feasible, because of their tendency to take on various meanings. Schumpeter preferred to "…say simply what we mean: economic life changes" (Schumpeter 1982, 64).

how scholars address important questions of public policy, particularly relating to change processes in social systems. This dissertation applies the theories from complexity theory, or complexity economics, to the study of standardization. This chapter provides a review of the seminal literature and situates these ideas in the context of this research agenda.

The Fundamental Tradeoff between Order and Flexibility

As defined in this dissertation, standards are a document designed to establish order, and the process of standardization is the process in which standards are created and implemented. This process inherently creates tension as standards may limit the generation of technological variety, and it is precisely on variety that long-term progress depends (Metcalfe and Miles 1994).

ISO's definition of standards emphasized the search for the "optimum degree of order" in a given context. The term order is used interchangeably in colloquial speech with several other terms—resilience and stability—therefore, it is worth differentiating between them. Stability here is used to refer to an artifact or process that is consistent through time. Stability is not conditioned on complexity—simple systems can be unstable and complex systems can be stable (Turner 1997). Resilience refers to the ability to reconstruct following a dynamic change.

Interest in social order has been of longstanding concern to philosophers. In Hobbes' description of social order, the coordinated actions of individuals, through governance structures, alleviates the human suffering that occurs in purely natural environments—that is, a state of nature. In the Marxist tradition, order, or social order, was maintained by the ruling class ideology imposed on the working classes.

Modern sociologists treat social order as the extent to which people comply with social norms. Parsons (1937), for example, believed that, the deeper the shared norms and values, the stronger the system.[15] However, a system can have order but not be resilient.[16]

In the networked economy, standards establish order by increasing compatibility at critical transition points. As Paul Agnew, an advocate of standardization efforts, pointed out, compatibility standards resolve the difficulties that arise "at the transition points—points at which the product passes from department to department within a company, or is sold by one company to another or to an individual" (Agnew, quoted in Murphy and Yates 2009, 7).

Modern supply chains require compatibility between numerous components. Incompatible standards can lead to bottlenecks at transition points, such as ports of entry where cargo from one country is transferred to another. Standardized interfaces allow firms to balance order and flexibility across the entire trading network, which today can span across multiple countries and continents.

The Functions of Standards

Several functions of standards are relevant to this dissertation. One of the primary functions of standardization is to facilitate cooperation and coordination among economic agents in order to reduce the costs of economic transactions (Kindleberger 1983).

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[15] Parsons' theory, now known generally as action theory, specified four minimum conditions for state survival: (1) adaptation; (2) goal attainment; (3) integration; (4) latency. The latter two components focus on the degree to which norms are shared (integration) and how they are transmitted between generations (latency).

[16] In August 2003, approximately 50 million people lost power in the Northeast U.S. The existing voluntary standard system was eventually singled out for reform. Although the energy grid was standardized, it was not resilient in that instance (Minkel 2008).

Standards also help different things work together by certifying compatibility, or interoperability, between components, and they facilitate modular frameworks for production. Certain types of standards, such as the quality management standards produced by ISO, may alleviate asymmetric information problems by serving as a "Good Housekeeping seal of approval" (Clougherty and Grajek 2012; Guasch et al. 2007).

Finally, standards can serve as a store of knowledge. There are two types of knowledge in the literature (Foray 2006). Following Michael Polanyi's seminal work (1966), knowledge is identified as either implicit (tacit) or explicit (codified), two distinct forms that are closely related. Tacit knowledge is generally learned by doing or through research, and it must be written down or otherwise documented in order to be shared and disseminated (Benezech et al. 2001). Tacit knowledge is frequently identified as the main driver of entrepreneurship, but it cannot easily be transmitted without access to knowledge creators (Polanyi 1966).

Codification is a process for expressing, routinizing, and embedding knowledge into infrastructure (Kahin 2004, 59). Codification-based infrastructures, like science and technology, are characterized by internal cohesiveness based on standards, evolved institutions, and professional practice (2004, 39). These infrastructures are concerned with making knowledge accessible in a variety of forms. Codified knowledge is more important for economies that are not at the technological frontier because it can be disseminated easily and is not constrained by geography.

Standards constitute one form of knowledge codification, what Cowan et al. (2000) refer to as a codebook. Standards can be used to formalize the tacit knowledge held by people and firms. As a result, technical standards are very important for the diffusion of new technologies (Swann 2010). Unlike patents, which can restrict others from using specified technologies, technical standards are usually public goods that can be widely used and that increase the productivity of other input factors (Blind and Jungmittag 2008).

Cesar Hidalgo (2015, 177) describes the importance of creating documents to store and codify information, a process he refers to as the creation of "solids," which are necessary to store information so it endures. Sidney Winter (1999) states that an important question in the evolutionary approach is "where is the knowledge stored?" Winter began to answer this complex question:

> "an important locus of storage is the memories of the personnel who perform the relevant routines, also their machines and tools, and the physical layout of the production site. Nowadays, computer programs are an increasingly important form of storage. These loci of storage -- as contrasted with others that are not bound to the spatio-temporal setting of a particular organization -- are particularly crucial to the margins of superiority that account for competitive advantage, or for the height of the entry barriers protecting incumbent firms" (Winter 1999)

The timing of when standards are introduced can also affect their effectiveness. They may be introduced too early, before markets have had a chance to work out what technologies are optimal. This can be another cause of lock-in.[17] Conversely, standards may be necessary at an early stage, when they can facilitate or lead a market, make a market possible, or be a prerequisite for the implementation of ICT technologies (Baron

[17] Lock-in refers to when a standard or dominant design is chosen and becomes resistant to change.

and Schmidt 2017). The Internet protocols, for example, were a necessary prerequisite for its development and later commercialization.[18]

To better understand the role of standards in creating order, the next section addresses how ideas from complexity theory and evolutionary economics may be applied to the study of change and the balance between order and diversity.

Change Processes

Schelling (1971) showed that an individual's actions can lead to system level changes, that is, that micro-motives can lead to macro-level changes. These emergent properties of systems are an important distinguishing characteristic of complex systems. The standard-setting ecosystem encompasses several different layers. Standards can be introduced by firms, associations, and national and international standard-setting organizations. Interaction of agents leads to more novelty and new behavior, which in turn leads to new institutions and organizations (Root 2013). Actions taken, or foregone, affect the different institutions in the standard-setting ecosystem. The interaction between national level organizations, like ANSI and BSI, has affected how ISO operates.

These networked interactions occur on a fitness landscape, a concept from evolutionary biology, which is a "conceptual basis for visualizing problems of

[18] The five layers of the Transmission Control Protocol and Internet Protocol (TCP/IP) stack are: applications, transport, Internet, link (or routing), and physical. The Internet Engineering Task Force (IETF) defines the standard in RFC 1122, *Host Requirements*, and defines four layers. Authors frequently refer to the Link and Physical layers separately, although in RFC 1122 they are considered one layer. The modular design of the protocol stack allows engineers to design standards for one stack independent of the others. Thus, at the application level, for instance, the W3C can focus on web design and applications standards like HTML and CSS. This allows for an efficient division of labor in standard creation and allows firms within standard-setting organizations to develop expertise at a given layer.

optimization or adaptation (problem-solving) with a given environment" (Root 2013, 239–40).

Evolutionary theorists study the adaptations of organisms through genetic changes. Through mutation, selection, and random chance, organisms are pictured by biologists as wandering through a landscape with higher and lower fitness levels (Frenken 2006). The fitness landscape, when applied as a metaphor to the social sciences, refers to the distribution of fitness values of different designs within a design space (Frenken 2006, 12). Changes in design, such as adopting new organizational routines, may lead to a higher peak, which signifies higher fitness, or it can lead to a lower peak and reduced fitness.

Changes in a fitness landscape do not occur in a vacuum. Individual actions by agents create shifts in the landscape and alter the constraints on others, as well as their opportunities. Through networks, adaptation, and evolution, new system structures emerge and continually shift. Evolution typically adjusts slowly to improve fitness, because the agent's prior actions, and the prior actions of other agents, constrain possible future moves.

In a complex system like the economy, path dependence frequently affects the trajectory of change processes (Arthur 1989, 2013). Colloquially defined by the term "history matters," path dependence implies that current decisions are influenced by previous actions and decisions. Furthermore, even small initial choices may be amplified over time and may generate inefficient outcomes over a sufficiently long period of time. If consumers initially choose one product or platform, the property of increasing returns suggests that positive feedback will amplify the success of the product, even if a competing product or service performs comparably (Arthur 1989). Increasing returns is the mechanism of positive feedback that operates within markets to reinforce success or accelerate decline (Arthur 1996, 100).

Whether endogenous or exogenous, prior choices constrain the future set of choices. This sensitivity to initial conditions affects the path of evolutionary technological change. Thus, actors' seemingly small initial decisions can have persistent effects. In certain cases increasing returns can result in technological lock-in, in which a standard or dominant design is chosen and becomes resistant to change (David 1985). Lock-in can occur when new inventions come under the care of large organizations, stabilize, and then acquire momentum as components of large technological systems (Hughes 1987, 58).

Political and social phenomena often exhibit similar properties. Some of the alternative ways of organizing economic behavior have proven particularly disastrous, while others have led to unparalleled prosperity. The search for an optimal design (high peak) is sensitive to the starting point of a state and constrains the potential path for reform. Efforts to replace one set of institutions with another are unlikely to be successful without recognizing that the initial conditions matter. On the fitness landscape, it is possible to reach a higher plateau through small or large jumps, but as the size increases the probability of reaching a higher peak diminishes.

Diversity

In the complex adaptive systems approach, agents are diverse and their behavior is heterogeneous (Axelrod and Cohen 2001). This variation is one source of output diversity. A second source of variation is combining existing ideas and artifacts to create something new. Finally, as products and processes evolve through various feedback mechanisms, such as responding to user requests, they fill niches.

The processes of invention, innovation, and diffusion are not completely separate stages; they instead involve considerable interaction and feedback between stages, which shapes how technology evolves (Metcalfe 1994). Standardization "facilitates the creation of temporary stability or lock-in, to enable agents to coordinate their activities in a context of rapid change" (Foray 2006, 44). This temporary lock-in is portrayed as reducing variety, but it also provides a useful function as new products are introduced.

New technology adapts to meet local needs as it spreads across geographic space, and as entrepreneurs find new ways to utilize that technology. In complex systems, diversity and the creation of niches can ensure system stability. However, in the context of innovation, too many alternative firms pursuing alternative platforms may slow growth, since each firm is working to advance a private goal. Standard-setting organizations and the standards they create are one mechanism for constraining duplicative innovation.

Markets create order out of this system through a process of self-organization. In markets with increasing returns, a successful firm can create its own ecosystem by creating and maintaining a general-purpose technology. General-purpose technologies reduce diversity but provide a shared interface built on strong network effects, which allow many potential innovators to access a common platform (Arthur 2011; Simcoe 2012). This can reduce entry costs and enhance the value of the platform when the network is supplied by a large and diverse community.

The economy thus creates mechanisms that both increase and decrease variety and diversity. Possible paths for the development of new products and processes are constrained by prior actions, but the design space is nonetheless vast. Herbert Simon and Joseph Schumpeter both focused on the design space and its role in the innovation ecosystem.

Simon (1996, 3) defined artifacts as man-made systems of elements that meet a goal: “A forest may be a phenomenon of nature; a farm certainly is not.” The corn and cattle of the farm were devised of human ingenuity to meet our needs. An artifact, such as a car, can be designed in many ways. The total options for how to design an artifact, even if currently unknowable, constitute the total design space. The Gutenberg press is a classic example of a combinatorial innovation. Each of its components had been developed prior to Johannes Gutenberg’s tinkering; his innovation was in putting the disparate components—the movable type, ink, paper and the press itself—together and showing that his prototype could work by printing his first Bible in the 15th century (Johnson 2010b).

In *The Theory of Economic Development*, Schumpeter wrote (1982, 14): “Technologically as well as economically considered, to produce means to combine the things and forces within our reach. Every method of production signifies some definite combination.”

He believed that fundamentally new and shocking innovations were rare and that most new innovations combined elements of existing technologies and ideas. Throughout his writings, Schumpeter stressed the importance of innovation rather than invention. He emphasized that inventors in some cases might also become entrepreneurs, but that in general it is wise to treat the two as separate. He stated that “the inventor produces ideas, the entrepreneur ‘gets things done’” (Schumpeter 1947, 152). As a result, the process of converting an invention into a new innovation requires the successful transfer of knowledge between the person with technical knowledge and the entrepreneur, who has expertise in markets (Auerswald 2007).

Stuart Kauffman (1996) refers to this type of change process as the adjacent possible. Each new discovery opens up the possibility for new discoveries, and each new idea can be combined with an existing idea to form something new. Not all of these designs will be workable or useful, however. One problem with idea recombination is that economies may produce too much of a good thing. Some new product innovations are useful, but duplicative R&D efforts may be wasteful. We remember the Gutenberg Press but not the prior inventions that failed.

In ecological terms, the possible design space is so large that there are too many possible permutations to be functional. This limits the evolutionary fitness of a species and creates the risk that evolution will create a new combination (in this case of cells) that decreases fitness or may even lead to the extinction of the species.

In social systems, such system wide disaster is unlikely, but too much variation may still be problematic. In his history of the British Standards Institute (BSI), the

National Standards Body (NSB) of the United Kingdom, Woodward (1972, 9) notes that among the first standards published by the Engineering Standards Committee, the forerunner of BSI, was one that reduced the number of sizes of tramway rails from 75 to 5. At the time it was calculated that this reduced production costs by approximately £1 million per year. By the end of WWI there was growing consensus that there were too many duplicative standards. The movement to reduce duplicative standards can be achieved through different mechanisms. Standard-setting organizations can institute a standard, users in the market can settle on a standard, or it can be imposed by the government. One approach to the study of standardization is the theory of dominant designs, which seeks to understand how certain industries settle on standard products.

Dominant designs are an important concept from the study of technological discontinuities. Utterback and Abernathy (1975) presented a model of technological change that is dependent on standardization and Abernathy (1978) introduced the concept of dominant designs (Sahal 1981). A dominant design "is a single architecture that establishes dominance in a product class" (Anderson and Tushman 1990, 613), and the term can apply to new processes as well as product classes.

In the Utterback and Abernathy model, new product and process innovations follow a similar trajectory. First a new product or process is introduced, usually in response to a perceived need rather than as a result of a new scientific breakthrough. After the introduction, the new product undergoes a period of maturation and standardization. Finally, as improvement becomes increasingly difficult, systemic change will be pursued only when existing needs are not being met or a new technology induces change. At this final stage, any new changes are frequently revolutionary rather than evolutionary, and therefore tend to restart the process.

Anderson and Tushman (1990, 606) refer to these stages in the technology cycle as the era of ferment and the era of incremental change. In the first period, a technological discontinuity in the way a product is produced or in a new product creates a period of design competition and substitution that lead to new ways of organizing economic behavior. The second phase is marked by the rise of a dominant design followed by incremental innovation.

Anderson and Tushman (1990) looked at the emergence of dominant designs in cement, container glass, flat glass, and minicomputers. Their results suggest that the time required for a standard to achieve 50 percent acceptance varies by industry and within an industry. In the case of cement the time to a new standard varied between five and eight years following a new discontinuity. The rotary kiln, for example, was introduced in 1892 and displaced the existing method of making concrete in vertical kilns. The new method became a de facto industry standard in 1900. In 1903 a new method of producing concrete was introduced, and this method became a standard in 1910. This early period of innovation was followed by a long period of order and stability before a computerized method was introduced in 1960 and standardized in 1965. Standards in container glass took 11-15 years, while two examples in minicomputers took only five years. Simon (1996, 196) found that complex systems will evolve from simple systems faster if there are stable intermediary forms than if there are not. Thus, standardization is an important component of the innovation process.

The rise of the Ford motor company is illustrative. Ford quickly became the fastest growing auto maker, due to Henry Ford's relentless cost-cutting. Ford was able to offer a continual decline in price, while improving product quality. The price of a new Model T dropped from $850 in 1908 to only $290 by 1924, in nominal terms. By 1921, Ford accounted for more than 55 percent of all autos sold in the United States (McCraw and Tedlow 1997, 274).

Henry Ford attributed his success to the standardization of the entire production process. He was a great proponent of standardization and believed that "machine production in this country has diversified our life, has given a wider choice of articles than was ever before thought possible—and has provided the means wherewith the people may buy them … Standardization, instead of making for sameness, has introduced unheard-of variety into our life. It has been surprising that this has not been generally perceived" (McCraw and Tedlow 1997, 273).

Organizational change

The final application of complexity theory is to the management literature. This approach is an effort to get inside the "black box" of innovation policy and understand how a firm or an individual turns raw inputs into finished outputs. One of the important ideas here relates to the codification of knowledge through the routines of firms.

In the complex systems approach, the economy is assumed to be out of equilibrium in most instances, which means that firms must learn how to produce by trial and error (Arrow 1962). They do so by executing code at an organizational level, and in doing so they create unique ways of solving problems (Auerswald 2017, 117). This code—the routine actions of firms—are referred to as recipes by Winter (1968) and Romer (1996); Chandler (1992) refers to it as organizational capabilities; Nelson and Winter (1982) refer to it as routines; and Auerswald et al (2000) refer to code as production recipes. The terms are all trying to understand the same phenomena and may be used interchangeably.

Given the limitations of human cognition (H. A. Simon 1956), routines are an essential aspect of human action for two reasons. First, they allow each individual to preserve scarce decision-making resources for application to non-routine decisions (Nelson and Winter 1982), and second, they allow other individuals to economize on scarce decision-making resources because they can make reasonable predictions based on observations of their routines (Sarasvathy and Dew 2005, 153).

Lewis (2005) chronicles how standards and routinization have affected productivity levels in residential construction in Japan. In contrast to the United States, which settled on the 2x4 as the foundation for homes in the 1920s, Japan uses a post-and-beam construction method.[19] This approach is not as efficient to begin with, but it is further complicated by approximately 150 different production systems. As a result, production takes place on a piecemeal basis. Homes are frequently built differently, even by the same construction firms, and workers never gain the tacit knowledge that accrues through learning by doing. Without the repetition that American construction workers

[19] Prior to settling on 2x4 construction, the U.S. was locked into post and beam construction as well, which was the dominant construction method for millennia until the discovery of balloon frame construction (Busch 2011)Though it took a few years to transition away from the prior routine, the benefits accrued quickly due to lower skill requirements for labor and because a lesser amount of wood was required for production. Path dependence is an important force as emphasized by David (1985) but when the benefits are clear new standards frequently displace old.

experience, specialization never emerges. Lewis (2005, 38) estimates that labor productivity in the Japanese residential housing market is only 45 percent as productive as in the U.S.. One takeaway of the ad-hoc approach to managing resources and creating outputs is that productivity levels range widely even within the same industry (Bloom et al. 2014).

One outstanding research question is the degree to which routines match up with specific types of standards, such as the quality management standards produced by ISO. The ISO 9000 series standards include a number of important functions, such as documenting the production process and measuring how it is implemented. While the costs of certification are high, the benefits of firms in both developed and developing countries adopting ISO standards are slowly being acknowledged.

Now that some of the concepts of complexity theory have been introduced, it is worth revisiting the concept of order. Stuart Kauffman (1993, 29) describes several types of order, but he focuses on the importance of order at the "edge of chaos".[20] Kauffman's motivation for understanding order is a desire to understand how complex systems are able to adapt to mutation and selection, and are able to coordinate complex, flexible behavior and respond to changes in their environment.

Kauffman identifies two extreme categories of order relating to co-evolutionary systems. The first is the "Red Queen Effect," taken from when the Red Queen says to Alice "you have to run faster and faster just to stay in the same place!" (cited in S. A.

[20] The phrase "edge of chaos" is attributable to Doyne Farmer, in reference to Christopher Langton's studies of cellular automata.

Kauffman 1995, 125).[21] In this regime the species keep evolving in a never-ending race to sustain their current fitness level, and chaos prevails.

The second scenario is an evolutionary stable strategy in which a species is better off not changing its survival strategy, provided the other species it is co-evolving with follows its current strategy. The result is an equilibrium, or a resting point, where further change is suboptimal (S. A. Kauffman 1995).

In both of these systems the overall fitness is low. Improvements could be made but are not because they are each in a type of equilibrium. Kauffman (1995) describes a third path between these two states, which he terms "order at the edge of chaos." There is a position in the transition phase between the two low fitness states that allows for a more rugged landscape, with the potential to attain higher fitness.

The edge of chaos relates directly to the tension between standards and novelty. If an evolutionary system is too resistant to change, it will not be able to manage in the face of change; conversely, if a system is overly sensitive to change, then small changes will have disproportionately large consequences (Beinhocker 2007, 158). One function of standards is to ensure that the innovation system is generally orderly, generally adaptable and that small changes lead to small mutations.

The Balance of Costs and Benefits of Standardization

Standards can create costs and benefits. Some costs are obvious, such as if a firm invests in a technology like Betamax or HD-DVD, only to lose a standards battle to a rival. Alternatively, some firms have adopted a standard and subsequently become

[21] The original quote from *Through the Looking Glass* is: 'Now, *here*, you see, it takes all the running *you* can do, to keep in the same place. If you want to get somewhere else, you must run at least twice as fast as that!'

resistant to change. Beyond the costs to a firm however, there is a deeper philosophical question that has not been adequately explored in prior research. There are important tradeoffs regarding the speed of standard-setting, how severely standards limit diversity, and how the process is managed, that merit further exploration.

Since the onset of the second industrial revolution, the standardization process has, at times, emphasized efficiency and speed at the expense of harmonization and consensus. At other times standard-setting organizations have emphasized harmonization through consensus, even though the desire to arrive at consensus can slow the process of standardization. Standard-setting organizations have shifted priority in response to the underlying pace of technological change, although in doing so the architecture of standard-setting has had to adapt and evolve.

The study of institutional change and economic development mirrors debates in the natural sciences about how organisms emerge, evolve and adapt (Root 2017). The remainder of the dissertation applies these concepts to the question of how standard-setting institutions emerged, how they have adapted and evolved, and how they have balanced the tradeoffs and tensions between standardization and innovation.

CHAPTER THREE

The rise of private certification and standard-setting in health, safety, food production, and other important sectors has raised questions about who governs and regulates private activity (Rudder 2008; Rudder, Fritschler, and Choi 2016). National crises and scandals in various industries, from agriculture to accounting, have raised questions about the ability of private certification organizations, businesses, and nonprofit organizations to regulate and guide activity (Ranville 2014).

The recent focus on third-party governance and standard-setting is an important development that addresses gaps in the political science and public policy literature. Standard-setting organizations have helped shape the modern global economy, but they are relatively under-studied and under-theorized (Yates and Murphy 2007). Moreover, the recent literature discusses third-party governance as if it is a new phenomenon. There are in fact new organizations, such as the Forest Stewardship Council, that have a different social mission from the standard-setting organizations created in the late 19th century, thus, a historical understanding of private standard-setting may clarify current issues and enhance understanding of current organizational structures.

This chapter begins with a review of the second industrial revolution, a unique period in history and the first in which private, voluntary, and consensus-based standard-setting organizations emerged. Through emergent processes propelled by social, economic, and technological changes in the United States and Germany, the second industrial revolution transformed the functioning and operation of the global economy.

The research question for this chapter addresses a gap in the current literature. ISO describes standards as being documents designed to create the optimum order in a given context. This chapter examines the question of how individual engineers addressed challenges as the technology frontier was advancing and the composition of the economy and society was rapidly shifting.

Why Study the Historical Development of Standard-Setting Organizations?

In studying the early foundations of standardization activities, we may learn something about an important phenomenon that affects consumers today (Russell 2014, 2008). Furthermore, studying the creation and implementation of formal standardization processes is related to a broader discussion about institutional evolution and change processes in economic systems. Finally, understanding the origin and evolution of standard-setting organizations can inform the current discussion about the role of private organizations operating in the public sphere.

The origin of standard-setting is a topic of interest because the institutional framework established in the late 19th century persists and continues to influence how standards are produced today. The former Congressional Office of Technology Assessment (OTA) has advised that, to understand the structural changes and the demands on the modern U.S. standard-setting process, we must first look at the evolution of standards within the U.S. economy and the institutional arrangements that have promoted their development (OTA 1992, 39).

OTA (1992) reviewed the origins of standard-setting in order to understand modern standard-setting activities and how the U.S. system of production compares to European systems. Russell (2008, 2014) reviewed the origins of U.S. standard-setting in order to understand the emergence of open standards in information and communications technology (ICT) during the third industrial revolution.[22] Ernst (2015) sought to understand how the historical roots of our system affect our current policy, and how our system of voluntary consensus standards differs from systems in East Asia, particularly China. Krislov (1997) compared standard-setting in the United States, Western Europe, Soviet Europe, and Japan.

As with any attempt to glean lessons from history, we must be careful how we relate the findings. The challenges of development faced by the lower and middle-income countries today are not strictly analogous to the rise of the industrialized countries; developing countries face a different set of problems today than the U.S. or UK did in the long 19th century. As a result, we must be cautious in drawing inferences from these earlier examples.

The Second Industrial Revolution

The second industrial revolution has not been clearly defined by scholars, but it is frequently classified as the period between the U.S. Civil War and World War I (Gospel 2013, 4–5). [23] Prior to the Civil War, the U.S. was still in a period of geographic

[22] There are a number of different ways to classify the third industrial revolution. In (Agwara, Auerswald, and Higginbotham 2015), my colleagues and I define the third industrial revolution as the period from 1990 to the present and refer to it as the Algorithmic frontier. This approach is consistent with existing literature.
[23] This demarcation is useful because economic historians identify the period of 1870-1914 as the initial stage and the origin of the modern world economy (Goldin and Reinert 2007). Significant events include

exploration, so while early scientific inventions did appear during this period, the starting date for the second industrial revolution is usually around 1870.[24] This coincides with the creation of the first U.S. transcontinental railroad in 1869 and the closing of the American frontier.[25]

It also coincides with the Franco-Prussian war in 1870-1871 and the unification of Germany. The cluster of innovations in the U.S. also occurred in Germany. Germany's innovation in chemistry and its reliance on the railroad

The first reference to the era as a second industrial revolution appears to be in Patrick Geddes' *Cities in Evolution*, written in 1915 (P. Geddes 1915, 45).[26] For Geddes, the question was how global cities were changing and adapting to the forces of industrialization and the shift from agrarian to manufacturing economies. The term was popularized by David Landes (1969, 4), who described it as based on the "spectacular advances in chemical and electrical science and on a new, mobile source of power—the combustion engine." The cluster of innovations during the second industrial revolution was an important development, but this may be an incomplete description of the changes during this period. [27]

Japan's Meiji Restoration (1868), the Franco-Prussian war in 1870-71, and the subsequent unification of Germany (Pritchett 1997).

[24] This demarcation is useful because economic historians identify the period of 1870-1914 as the initial stage and the origin of the modern world economy (Goldin and Reinert 2007).

[25] In the 1890 census, the Census Bureau announced it would no longer track the westward migration of settlers, because by that point the frontier line was mostly gone.

[26] For a deeper examination of the history of the second industrial revolution see the work of James Hull (1996, 1999). For a fascinating exploration of the major technical advances during the second industrial revolution see Smil (2005).

[27] The second industrial revolution was a period of rapid innovation. In the 1870s inventors created automatic signals, airbrakes, and knuckle (Janney) couplers for railroads; telephones, electric lights; the application of the Bessemer and open hearth processes allowed for the mass-production of steel; and created the QWERTY typewriter, which is perhaps the most famous standard of all.

Robert Alexander Brady (1961, 5) identified four general characteristics to explain the scientific revolution:[28] (1) first was the chemical revolution that created new materials for industry; (2) second was the standards and specifications revolution in producing and selecting the best methods, processes, and products; (3) third was the creation of electronics and automation; and (4) fourth was the revolution in the systems of energy supply.[29]

Similarly, Gospel (2013, 4–5) lists four significant changes that help differentiate the period of the second industrial revolution from earlier history: (1) the emergence of large enterprises with hierarchical management structures; (2) the rise of science-based innovation; (3) changes in the skill of the labor force; and (4) new methods for hiring and training staff.[30]

Converging Developments

Like all countries, the United States has its own history of industrial development. The path taken by the U.S. reflected its values, ideology, and historical circumstances. Its development was also dependent on its physical size, raw materials, capital, and expanding labor force.

Inventions in the 1880s were focused on building materials, including the invention of the elevator, the use of structural steel for buildings, and the first skyscrapers. Among the innovations during the 1890s, inventors created the phonograph, the motion picture, electrical generation, refrigeration, washing machines, and the internal combustion engine.

[28] While his study covered the period until the mid-1950s, the typology applies equally to the second industrial revolution.

[29] By energy supply Brady was referring to atomic energy, however the industrial combustion engine and electricity were the emergent energy sources during the second industrial revolution.

[30] The new methods of managing staff will be discussed in greater detail in Chapter 5, in reference to the rise of quality management standards.

The second industrial revolution represented the confluence of several events including: the growth of the American population and the shift from rural to urban life; the rise of the corporate form; and the rise of science-based industry.

Clustering of People and Innovation

One unique feature of the second industrial revolution was an increase in the clustering of innovation. Two types of clustering are important: one relates to geographic movement and Americans' decisions about where to relocate; and the second relates to the close proximity of new innovative activities in terms of both geography and time.

First, consider the mass movement of people across the continent. Americans in the 19th century were moving westward, and by the end of the century they were also beginning to move to towns and larger cities. According to Simon and Nardinelli (2002, 60), the number of American cities with 10,000 or more people increased from 93 in 1860 to 752 in 1920; those with 100,000 or more people increased from 9 to 68.

The U.S. population rose from 5.3 million in 1800 to 38 million by 1870. By 1900 the population had surged to almost 76 million, and it surpassed 105 million in 1920, roughly consistent with the end of the second industrial revolution.[31]

The rise of science-based research and innovation, coupled with new science-based institutions, led to an increased concentration of economic activity in cities (C. J. Simon and Nardinelli 2002). Sokoloff (1988) demonstrated that inventive activity (as measured by patents in the pre-Civil War era) was concentrated around locations with cheap access to transportation, which became the carriers of innovation to new markets.

[31] Data from Table Aa1-5, *Historical Statistics of the United States, Millennial Edition Online* (available online: http://hsus.cambridge.org/HSUSWeb/HSUSEntryServlet)

The large U.S. market of relatively homogeneous consumers mattered because it induced firms to undertake the design and setup costs necessary for long production runs of standardized goods assembled from interchangeable parts (Romer 1996, 205). This made it economical to invest in specialized machine tools, for example. The scale of production also increased, as large firms began to encompass a greater share of the business landscape (Chandler 1977).

Second, the novel innovations were developed through a process of cumulative innovation. Contemporary technology was not only superior to that of prior periods, it created new artifacts not even conceived of during the previous era that could not have been built at any price using earlier technology (Landes 1969, 5).

The automobile and the airplane, for example, combined elements such as steel and engines to create entirely new goods—Schumpeterian recombination. Kauffman (1996) designates this type of innovation as the adjacent possible the automobile and the airplane depended on the prior innovations and could not have been developed without them.

In a current example, YouTube could not have been created before its 2004 appearance because it required later technology (such as Flash) and faster Internet connections (Johnson 2010a). If it had been introduced earlier, it would have been slow and unsatisfying to use and likely would have failed. In short, prior innovations unlocked the technology that enabled YouTube to gain billions of viewers.

The concept of the adjacent possible is similar to Schumpeter's notion of idea recombination. This is captured particularly well by Johnson (2010a): "The strange and beautiful truth about the adjacent possible is that its boundaries grow as you explore them. Each new combination opens up the possibility of other new combinations." One key to successful idea recombination that is apparent from this research is that new innovations were created after the initial period of discovery and ferment was over. This reinforces Simon's (1996) point that stable intermediary forms facilitate the development of complex systems.

The Managerial Revolution

The late 19th century saw the rise of the corporation as the driving force of innovation in the developed economies. This rise was a result of deliberations following the American Revolution about the proper role of political and economic relations in the nascent republic. U.S. law emphasized individual liberties and market-oriented relations while balancing an active government approach advocated by Alexander Hamilton, and later by Henry Clay and John Calhoun.[32]

Prior to the second industrial revolution, most Americans were self-employed rather than employees of firms. The early private companies that did exist were typically created to produce public goods, such as roads, bridges, and canals, and were modeled after the British system of chartered corporations. An important legal innovation was the creation of the corporation as a business organization with rights to own its property, transact business, and litigate for damages (Lehne 2006).

The corporate form evolved throughout the second half of the 19th century as the role of large-scale private enterprise increased. The era was defined by the rise of mass

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[32] Alexander Hamilton (1791), *Report on the Encouragement and Protection of Manufacturers*.

production, interchangeability of parts, power-driven machinery, and a rise in the volume of production as costs declined (Hounshell 1985). One result of this transitional period was a change in the composition of employment; whereas fewer than 15 percent of Americans were employed by industry in 1850, by 1900 approximately two-thirds had become employees (Lehne 2006, 8).

Although the country moved toward manufacturing during the second industrial revolution, its scale was dwarfed by the railroads, America's first big business (Chandler 1977, chap. 3-5). The Pennsylvania Railroad employed more than 50,000 people, which was more than the federal government employed and far surpassed the number of employees in the average manufacturing firm, which typically had fewer than 2,000 people (Lehne 2006, 9).

Private corporations were initially charted to provide a public good and a social benefit to society. This initial emphasis gradually gave way to the profit motive as the guiding force of the corporation, which also changed how profitable entrepreneurs were perceived (e.g., "robber barons"). The large concentration of wealth that accrued during this time was party recycled into American society through the creation of dedicated philanthropic efforts (Acs 2013).

According to Abramovitz and David (1973), the second industrial revolution was unique because of its sources of growth. They argue that the driving force of economic growth in this period was the shift of labor from agriculture to manufacturing and industrial work, and the concomitant increase in capital employed per worker.

New Standard-Setting Organizations

The first standard-setting organization, United States Pharmacopeia, was created before the second industrial revolution, in 1820. The first U.S. trade association was the American Iron and Steel Institute (established in 1855). Private governance of standardization activities began on a wide scale as a response to the rapid change and development that occurred in the period following the American Civil War. Along with this extensive development of standardization organizations was a growing concern that, since standards embody some attributes of a public good—what Tassey (1982) and Cargill (1996) refers to as infratechnologies—there might be insufficient development of standards and standard-setting organizations.

Robert Brady first proposed a path for convergence in standard-setting behavior by proffering several stages of development: (1) firm, (2) industry, (3) state; and (4) global (Brady 1929, 100). [33] Most engineering societies had standard-setting capabilities by the time the ANSI was formed in 1918. Most of these organizations created standards that were applicable to their membership but were not relevant across industries. The American Society for Testing and Materials (ASTM) was one exception to this trend because its standards were broadly applicable across industries (C. A. Adams 1956, 26).[34]

Impetus for National Standard-Setting Organizations

The U.S. standardization system emerged in the late 19th century, but early standardization efforts predated formal standard-setting organizations. Producers became

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[33] To this list it is important to regional standard-setting organizations, which have become prominent in Europe. In Europe these include the European Committee for Standardization (CEN), the European Committee for Electrotechnical Standardization (CENELEC), and the European Telecommunications Institute (ETSI).

[34] ASTM is now officially "ASTM International."

involved in standardization when trade was extended across the continent (Beniger 1986), a process enabled by the railroad.

It is worth taking a moment to appreciate the role the railroad system played in the development of America. Contemporary accounts provide a breathless review of the new machines that help establish perspective. Charles Francis Adams, Jr., for instance wrote:

> Here is an enormous, an incalculable force practically let loose suddenly upon mankind ; exercising all sorts of influences, social, moral, and political ; precipitating upon us novel problems which demand immediate solution ; banishing the old before the new is half matured to replace it; … but not many of those who deal in its securities, or live by means of it, or legislate for it, or who fondly believe they control it, ever stop to think of it as … the most tremendous and far-reaching engine of social change which has ever either blessed or cursed mankind (C. F. Adams 1871, 335)

Just a few years before completion of the transcontinental railroad, the Civil War became the first significant military conflict in which railroads played an important role in military logistics. The agrarian South, which was never as enthusiastic about railroads as the more industrialized North, was never able to cooperate in building a standardized rail system (ANSI 2014b). Private owners didn't want to share their track with competitors, and so they built proprietary rail lines that did not share a standard gauge (Civil War Trust 2017). The South didn't want to take away private ownership, and the Confederate rail system ran into trouble in just a few years. The North's naval superiority limited the South's access to the iron it needed for repairs, and as men left private rail companies to fight in the war, there quickly was a shortage of the wood the South used to fuel the trains' engines. In short, standards clearly played an important role in the Civil War, as the North's more sophisticated use of trains contributed to its eventual victory.

The dissemination of standards accelerated as trade extended across greater distances and became safer and more reliable. The national railroad system required new business organizations to enable joint and through operations.[35] Of particular note is that the bill of lading became business system's accepted method of billing across the country in the 1870s, which coincided with the railroad's increased reach (Kirkland 1967, 49). Norms had to be established to ensure that freight and passenger rail systems could intermingle, and that shippers and passengers could depend on reliable printed schedules. Actual paper schedules were created to facilitate these processes.

In addition to facilitating trade, the railroad brought with it new forms and standards of business activity. The limited trade that occurred between early settlements during the westward expansion was predominantly agricultural. When farmers moved west, they labeled their products by their place of origin. This served as a mark of quality and could be successfully marketed—an early form of brand recognition.

The railroads also required technical standards to ensure that material specifications were of good quality. The locomotive builders, steel-rail producers, and steam-engine builders relied on new materials and processes, such as the Bessemer steel process, which required new knowledge and technical expertise (ASTM 1998). The

[35] To reduce cost and to ensure access, owners of railroad track (the "owner") established sharing agreements so another railroad ("the tenant") could use the same track (a "joint facility.") (Blaszak 2006). A through operation refers to the process of allowing a train to run unimpeded even as the operator of the line, or the owner of the line, change at specified times. One rail operator had to know its trains could run on another's track and that its weight would be compatible across the other owner's bridges, tunnels, and train station dimensions.

producers had practical knowledge about the cost structure and knew more about practical production issues but did not have a good understanding of steel's long-term performance and were hesitant to defer to their customers. The need for testing and standardization was thus of crucial importance because it could become a mechanism to bridge the knowledge gaps between supplier and user and result in improved products.

Charles Dudley, a chemist at the Pennsylvania Railroad, helped overcome the initial resistance to testing and standardization among producers. Dudley proposed the formation of technical committees, with representatives of the main parties, to discuss every aspect of specifications and testing for new materials (ASTM 1998, 31). Out of his frustration with Pennsylvania Railroad's suppliers, Dudley was gradually able to build consensus and his efforts contributed to the formation of the International Association for Testing Materials (now ASTM). The rise of testing was a response to the implementation of new innovations (new processes for making steel, new end uses in rail and railroads) and engineering-led tinkering.

The need for standardization became increasingly clear as firms developed greater capabilities. There were several primary drivers of the standardization movement during the second industrial revolution. One driver was to increase compatibility between firms and others included the movement toward interchangeable parts and the development of the so-called American System of Manufacturing. Finally, standardization played an important role in reducing variety.

The new standard-setting institutions at the firm and industry level were a response to a growing need. Private governance of U.S. standardization activities began as a solution to the rapid change and development that occurred in the period following the Civil War. Firms and industries were seeking a balance between the rapid change in the system and the proper balance of order through standardization. As Cargill (1996) notes, as the degree of industrialization increased, so did the amount of interdependence required for the elements of society to cooperate successfully.

The natural inclination among Americans at the time was to find a private solution to the rise of interdependence. The federal government was limited in size by both social preference and financial limitations, since its taxing powers were limited. De Tocqueville recognized the Americans' reliance on private associations to solve governance issues: "Wherever at the head of some new undertaking you see the government in France, or a man of rank in England, in the United States you will find an association" (cited in OTA 1992, 20).

Third-party governance of standard-setting activities was also necessary because of the scale involved—there are simply too many standards to legislate or authorize through rulemaking. Olle Sturen estimates that a modern economy requires approximately 20,000 standards (Brunsson and Jacobsson 2002). Moreover, standards must not only be created, they must be updated and maintained (Russell and Vinsel 2016). When a government institutes standards, they exist for decades or generations, often without revision or updates.

Innovation depends on the infrastructure of standards and regulation. The private standard-setting organizations that emerged during the second industrial revolution were one response to growing disorder. While these organizations did limit variety through their standards, their limited efforts provided a guide for innovative activity.

In early pre-industrial societies, economic interactions were often regulated by family relationships and codes of human behavior. Private guilds provided some loose standardization activities, but most standard-setting activities resided with the state. The second industrial revolution saw the creation of standards as a response to mass production and increased specialization, particularly with respect to scientific innovations, which required accurate measurements and consistency. Standards and mass production were self-reinforcing complementary activities driven by positive feedbacks. Advances in precision manufacturing required the development of machine tools and precision gauges, which drove the need to standardize these tools (e.g., calipers with a vernier scale; OTA 1992, 40).

Standards facilitated cooperation, but the disparate nature of the standard-setting organizations led to growing interest in a higher order organization to coordinate their actions in order to minimize duplicative efforts. This process is detailed in the next chapter.

CHAPTER FOUR

Once domestic trade associations and standard-setting organizations began to operate in foreign markets it became clear to a number of national governments that they could help domestic firms if they could have their nation's proprietary standards adopted.

The British Standards Institute (BSI), the world's first national standards body, was formed by the mutual agreement of existing engineering societies in 1901 (e.g. civil, electrical, and mechanical engineers; Murphy and Yates 2009, 11). The American National Standards Institute (ANSI) was formed in the same way in 1918.[36] The rise and success of national standard-setting organizations created growing interest in harmonizing standardization processes globally. Momentum began to grow for one institution to manage the process internationally.

Convergence in Standard-Setting Institutions

Three principal forces motivated countries to adopt national standard-setting organizations. The first force was the observation by engineers and other technocrats that the current system of decentralized standard-setting was inefficient and was not satisfying the existing technological needs. The second driver was the central role the UK was playing as part of a network of industrialized nations. Finally, the period prior to World

[36] ANSI was originally founded as the American Engineering Standards Committee by five engineering societies and the U.S. Departments of War, Navy, and Commerce. It was renamed the American Standards Association in 1928 and the United States of America Standards Institute (USASI) in 1966. ANSI adopted its current name in 1969 (ANSI 2017a)

War I saw trade flows increase rapidly across continental Europe and among a growing network of global trading partners. This process was slowed by World War I, but Germany, France, and many Northern European countries created standard-setting organizations not long after the war's end.

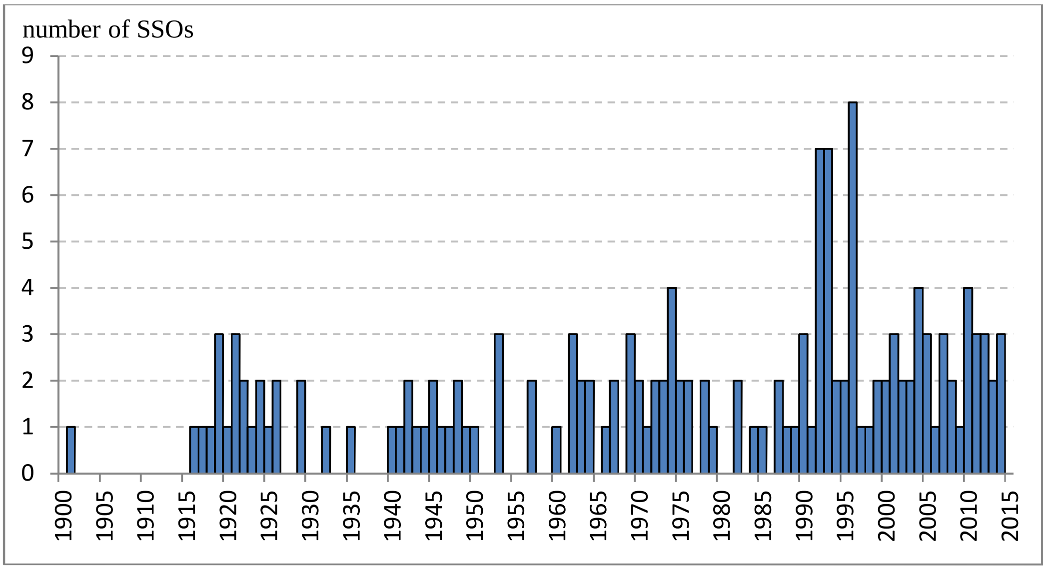

Figure 1 - Initial Year of National Standards Body

The period between the two world wars saw the creation of 23 national standards bodies, roughly 10 percent of the 163 current member of the International Organization for Standardization (ISO).[37] These first institutions represented two primary groups: the industrialized economies of Western Europe and the United States and a group of Eastern

[37] There are three types of ISO membership. According to ISO: Full members (or member bodies) influence ISO standards development and strategy by participating and voting in ISO technical and policy meetings. Full members sell and adopt ISO International Standards nationally. Correspondent members observe the development of ISO standards and strategy by attending ISO technical and policy meetings as observers. Correspondent members can sell and adopt ISO International Standards nationally. Subscriber members keep up to date on ISO's work but cannot participate in it. They do not sell or adopt ISO International Standards nationally (ISO 2017d)

bloc nations affiliated with the Soviet Union (USSR). Argentina, which was a comparably prosperous nation at the start of the 20th century, also established its national standards body during this period.

Table 1 - National Standards Bodies Created in the Interwar Period

Country	Organization	Date of Incorporation
United States	ANSI	1918
Belgium	NBN	1919
Canada	SCC	1919
Czech Republic	UNMZ	1919
Switzerland	SNV	1919
Austria	ASI	1920
Hungary	MSZT	1921
Italy	UNI	1921
Japan	JISC	1921
Australia	SA	1922
Sweden	SIS	1922
Uzbekistan	UZSTANDARD	1923
Finland	SFS	1924
Poland	PKN	1924
Russian Federation	GOST R	1925
Denmark	DS	1926
France	AFNOR	1926
Portugal	IPQ	1929
Turkmenistan	MSST	1929
Turkey	TSE	1930
Kazakhstan	KAZMEMST	1932
New Zealand	NZSO	1932
Argentina	IRAM	1935

A second wave occurred following WWII, as the old system of colonialism gradually waned and new institutions were created. These included the General Agreement on Tariffs and Trade, or GATT, and later the World Trade Organization

(WTO). The Agreement on Technical Barriers to Trade (TBT) was first negotiated in the Tokyo round of GATT, and was later incorporated into the WTO during the Uruguay Round (Guasch et al. 2007). The TBT, which was designed to reduce trade barriers arising from the promulgation of standards, became binding on all member states, which created an incentive to develop a national standard-setting organization as an interface to the WTO, if one was not already in place. To participate in these formal processes, a country was required to have a national representative body. This led to new standard-setting organizations being established at a steady pace, particularly in developing countries eager to participate in new trade agreements, which were another important impetus for creating standard-setting bodies.

In the span of a century almost all countries created a national standard-setting organization to manage the process of standardization. This rapid and phenomenal convergence to an organizational form did not mean that all organizations were the same, although they tended to take one of three principal forms: (1) private; (2) hybrid private/public; and (3) government. Approximately 80 percent are a hybrid form (Mendel 2001, 46). As an example, the British Standards Institute is a private company incorporated by Royal Charter.

The presence of government-run standard-setting institutions is in part a legacy of the USSR, which focused on the development of standards to ensure quality in a nonmarket setting.[38] The standardization paradigm adopted by the USSR was part of a longer process that began under the czars to hasten industrialization (Shaevich 2001). In

[38] In reality, the Soviet system emphasized production quantity and not quality (Krislov 1997).

the USSR and its Eastern European satellite states, the standard-setting process was a completely top-down, state-run activity (Krislov 1997).

By contrast, the U.S. standard-setting process reflects longstanding political and cultural bias that favors the marketplace (OTA 1992). The American system of standardization is distinguished by its diverse and fragmented character that mirrors the broader American trend of relying on a liberal market economy (Russell 2005). In contrast to many other countries, the “standards development organizations in the United States first emerged in the private sector, in response to specific needs and concerns” (OTA 1992, 39). In fact, most standard-setting activity in the United States is carried out through private organizations. ANSI is a private non-profit organization that coordinates and accredits U.S. standard-setting organizations. It also coordinates international standard-setting activities and is the representative to ISO and the International Electrotechnical Commission (IEC).

The American Engineering Standards Committee (now ANSI), created in 1918, was formed on the mutual agreement of five organizations, all created during the second industrial revolution: the American Institute of Electrical Engineers (now IEEE, 1884),[39] the American Society of Mechanical Engineers (1880), the American Society of Civil Engineers (1852),[40] the American Institute of Mining Engineers (1871), and the American Society of Testing and Materials (1898). These five organizations subsequently invited the U.S. Departments of War, Navy and Commerce to join them as founders.

[39] The Institute of Electrical Engineers is a professional association, formed in 1963 from the combination of AIEE and the Institute of Radio Engineers.
[40] The American Society of Civil Engineers was created during an earlier era but languished until it was reorganized in 1867 (Calvert 1967, 109).

These organizations were created to manage the process of standardization in their respective industries, but their missions were frequently broader.

The U.S. government also plays an important role in standard-setting. The Department of Defense has traditionally been the largest developer of standards in the federal government, although its presence is slightly reduced since changes were made to reduce some of its proprietary standards (Tate 2001, 464). NIST is also involved in both the voluntary and mandatory sectors, with the aim of providing technical assistance to industry. Its historical application has been the establishment of reference weights and measures (Cochrane 1966). Most standard-setting activity in the United States is carried out through private organizations.

The British Role in the Diffusion of Standards Associations

One leading force for the promulgation of standard-setting organizations outside Western Europe was BSI and the UK government. Together they applied pressure throughout the British Empire to establish standard-setting organizations and capabilities in order to facilitate trade (Galbreath 1998, 209). The former British Crown Colonies were part of a network that relied on standardization. BSI integrated its colonies in the standardization process by organizing committees in each country. South Africa, for instance, established a committee to coordinate with BSI in 1908, and most countries created similar committees (Tate 2001). The open lines of communication helped the British communicate their expectations for quality and for the specifications of raw materials they relied upon. In turn, the coordination helped British industry find markets for its products, and this effect persisted after the deconstruction of the colonial system.

The UK's colonial network helped spread the influence of BSI's standards. Countries with close historical ties to the UK, such as Australia and New Zealand were among the first industrialized nations to create new standard-setting institutions at the national level—in 1926 and 1932, respectively. The U.S. and Canada, which also have close historical ties to England, established national standard-setting systems in 1918 and 1919 respectively. Other British colonies relied on the standards produced by BSI until they established their own systems following WWII.

The former British Crown Colonies created standard-setting organizations shortly after they achieved independence. Sri Lanka, for example, a colony known as Ceylon until 1972, established its national standard body (NSB) in 1964, while South Africa created its standard-setting body in 1945, India in 1947, Ghana in 1967, and Jamaica in 1969. However, not all former colonies immediately after achieving independence: the Republic of the Gambia was among the last to do so, in 2010.

National Systems of Standardization: The Chinese System

Because of China's large manufacturing base and its importance on the world stage, I present a brief case study of its emergent standards policy. As a transition country, China is an important case study. Its population is three times that of all other transition countries combined, and its economy is bigger than all transition economies combined (Qian 2002).

Furthermore, China aspires to be a world leader in science and technology and the capacity to influence the domestic politics of the developing countries in its periphery. Root (2013) observes that China's cultural properties mean it is not likely to adopt many elements of Western ideology, therefore, as it expands in new markets its presence is causing its partners to adapt to new conditions, a process that may eventually challenge and redefine system-level rules.

The conventional hypothesis in development economics is that despite different initial conditions relative to the West, countries should follow a similar development path. According to Sachs (2006, 41), "the single most important reason why prosperity spread, and why it continues to spread, is the transmission of technologies and the ideas underlying them." This implies that China needs to adopt new technologies to reduce its gap with the West. *The East Asian Miracle* (World Bank 1993) emphasized the importance of such innovation-led development.

China was a founding member of ISO but withdrew from the organization in 1953 following its civil war.[41] It rejoined ISO in 1978 as part of its broader reintegration with global institutions. China's standard-setting system is formally managed by multiple departments of the Chinese government and through the China Association for Standardization (CAS), which is a public society approved and led by the national government. The Standard Administration of China (SAC) is the representative to international standard-setting organizations like ISO and the IEC, and the WTO/TBT entry point.[42]

The standard-setting process is a key component of China's science and technology strategy. Economic and technological development in China is driven by a

[41] The civil war ended in 1949, at which point China relinquished its spot on ISO's council, and formally withdrew from ISO in 1953 (see

[42] The Ministry of Industry and Information Technology is the representative to the International Telecommunications Union.

series of five-year plans that began in 1953 (Yan 2004).[43] The initial system implemented policies that mimicked the USSR's bureaucratic and hierarchical R&D structure (Serger and Breidne 2007). The modernization of China's science and technology policy truly kicked off in 1982 with the National Plan for Tackling Key Problems of Science and Technology (Yan 2004).

China's short-term plans are supplemented periodically with a series of medium and long-term plans, the most recent of which was published in 2006. Entitled The National Medium-and Long-Term Plan for the Development of Science and Technology (2006-2020): An Outline (hereafter MLP), the plan sets out China's intention to become a world leader in several cutting-edge fields, such as information technology, biology, materials, and space. The plan specifically calls for the "construction of a national innovation system with Chinese characteristics." Operationally this goal involves strengthening the university system and dramatically increasing the number of scientists working on frontier technologies, by bringing university researchers together with enterprises and research institutes. Finally, the plan is intended to create industry and military links to promote dual-use technologies while protecting China's national interest.

China's relatively modest per-capita income means that Chinese consumers are only slowly starting to demand high-tech products that rely on tacit knowledge. As a result, firms in China have historically gotten by using existing standards without having to create their own standard-setting organizations or new standards. The MLP seeks to change this by creating markets through government procurement, and to encourage the

[43] The Chinese government purposively avoids the term "plan" in favor of "program," however plan is still used in many ministries and I use the terms interchangeably.

development of new standards both internally and within international standard-setting bodies. The sheer size of China's domestic economy and government purchasing power means it can be a force for the diffusion of new standards.

Backlash against the MLP from some members of the American business community was severe. McBride (2010), for example, wrote that China's indigenous innovation was "a blueprint for technology theft on a scale never seen before" (quoted in Kennedy, 2010, p. 15). Concerns arose that indigenous innovation was code for economic nationalism and that information security standards could be imposed on foreign firms in order to provide access to their private intellectual property (McBride, 2010). Combined with relative weak intellectual property rights protection, this has increased tension between the US and China (USTR, 2006).

China approaches the idea of standards from a fundamentally different position than the West due to three principal factors. First, China is still developing a truly viable system of private enterprise (Huang 2008; Wagle, Gregory, and Tenev 2000) and the firms that have prospered have done so amidst a tangled web of state support (Root 2013).

Second, unlike in the West, where standard-setting organizations are mostly nonprofit bodies that operate with the cooperation and coordination of private companies, in China the standards system is driven from the top in China (Ernst 2011; Kennedy, Suttmeier, and Su 2008) . The planning process establishes priorities for private firms, such as its own proprietary 3G or WAPI (an alternative to wifi), which must then undertake the research and development to meet the plan requirements and implement the standards (Kennedy, Suttmeier, and Su 2008). Finally, China viewed the adoption of standards in the 1990s with considerable unease. Therefore, the profits from becoming a manufacturing economy were not fully captured because foreign firms owned the patents, trademarks, and copyrights (Kennedy, 2010). The Chinese also have a fundamental distrust of international standards groups and China does not recognize all of them (Ernst 2011).

The MLP reveals China's recognition that frontier technologies will allow the country to leapfrog of development, a process that is now well underway.[44] This would not be the first time China pursued an aggressive policy of modernization. The "four modernizations" under Deng Xiapoing, represented a long jump forward on the fitness landscape. "Long jumps on a fitness landscape reflect radical innovation, implying the transition of one complex technological system to a new and very different one" (Frenken 2006, 20).

The new system in China has fundamentally altered the global system and may lead to a contest over the rules of the game. Increasing diversity, emergence of local niches, and an increase in global interaction mean the system is potentially unstable. As Bak (1993) notes, systems can be relatively stable until they suddenly reach a level of criticality, which may then be followed by a catastrophic event.

There is a widespread expectation that the success of the U.S. model of innovation and entrepreneurship will inspire more centrally-coordinated innovation

[44] China's development of artificial intelligence is almost equal to, or perhaps just beyond, America's capabilities, which has important ramifications for the development of autonomous vehicles, among other applications (The Economist 2017).

systems to converge towards its market-led system. However, existing comparative research on national innovation policies suggests that this type of convergence is limited (Nelson 1993; Tate 2001).

During the second industrial revolution there were new standard-setting activities in a number of industrialized countries. This process culminated after WWI when just over 20 countries created formal standard-setting organizations.

Standardization involves a mix of market competition, cooperation, and coercive elements. In practice, trade-offs between these properties do not present a clear picture of what is a good or bad economic choice (Greenstein 1992, 538).Therefore, the degree of diversity at the national standard-setting level does not reflect a divergence from a global optimum. It is instead consistent with evolutionary theory, which posits that actors and agents will search for local optima and will need to satisfice as a result of too little information. Path dependence and the initial conditions in a country will shape the formation and evolution of organizations and such systems will shape the formation and evolution of organizations. Such systems will tend toward increased diversity over time, as the organizations adapt to local needs. Standard-setting organizations will adapt to changes from higher levels in the system, just as BSI has adapted to changes in the system structure, but changes at BSI also affected ISO, as did broader technological changes.

Over the past century almost every country in the world has created a national standard-setting organization to support more specialized entities.[45] Countries with advanced liberal systems quickly adopted national standards, based on market competition. Less developed countries were more likely to depend on state coercion. Several countries in East Asia maintain government-run standard-setting systems, while only Portugal does so in Western Europe (Tate 2001). There is considerable diversity within each level of the standard-setting system. Although Americans might expect ANSI to serve as a model for other countries, it has not. America's system of standardization reflects the particular country characteristics in place at the time of its founding, just as BSI and the German Institute for Standardization (DIN) reflected the features of their societies at the time of their founding.

The founding members of each national standard-setting institution were trying to balance a difficult set of options: How many members should they allow? What types of members? Should individuals be admitted? Individual companies? Only organizations such as professional societies? What types of due process should be incorporated into the organizational design? The founders of organizations were not copying from an ideal but conducting a search for a reasonable institution that could balance multiple interests and instill some order, while hopefully encouraging innovative activity. The founders were not optimizing; in Simon's (1956, 129) terminology, they had to "satisfice.

[45] In this paper I looked at the national standards bodies of the ISO, but this underestimates the total number of standard-setting organizations in the world, because some countries do not participate. The IEC has more national members, as just one comparison. Nevertheless, all major countries have standard-setting organizations at the national level.

CHAPTER FIVE

> *If the quality revolution is as important as its proponents claim, it may well be the most important management innovation of the 20th (and early 21st) century. If its significance is only a fraction of what is claimed, it could still be quite important.*
>
> — (Simon Winter 1996, 460)

The modern era of globalization has led to increased economic interdependence and interconnectedness in the world economy (Acs and Preston 1997). One factor that drove this integration was the gradual development and evolution of hundreds of national standard-setting organizations. These organizations, while organized differently, shared the common mission of harmonizing standards across the widest possible space. The creation of the International Organization for Standardization (ISO), which represented the culmination of these trends, provided a fully functioning international infrastructure for standards development and instituted a formal mechanism for diffusing standards globally. The collaborative, albeit occasionally combative, nature of these organizations was enabled by the expertise of their membership.

Since the creation of ISO following World War II, there has been a consistent effort to harmonize standards and ensure compatibility and interoperability at the international level. The pursuit of harmonized standardization occurred concurrently with the growing diversity and complexity of global supply chains. The process of globalization was built on increasingly dense trade flows networks (Auerswald and

Branscomb 2008). Ricardo Hausmann and coauthors (Hausmann et al. 2012) have demonstrated how some countries have utilized global value chains to develop their domestic capacity. Their model estimates the productivity of complex traded goods.[46]

The desire to harmonize standards at the highest possible level increased the importance of organizations like ISO and the International Electrotechnical Commission (IEC) while also affecting more traditional organizations, like industry associations. The changes in the architecture of the standard-setting system have been driven by at least two distinct factors: (1) the growth of global economic integration through global supply chains and increased trade; and (2) the changing operational and managerial structure of firms.

First, the degree of global integration has occurred on an unprecedented scale. This is true if we look at foreign direct investment, trade flows, or the integration of labor and commodity markets (Bordo, Taylor, and Williamson 2005). Investment has increased alongside the opening of new markets.

Differing standards between nations constitutes a barrier to trade, raising both production and transactions costs. The presence of different standards in countries A and B mean that if a firm produces a standardized product for sale in both counties, it will have to customize production for each country and document standard compliance for each country.[47] A harmonized standard applicable to both countries allows greater

[46] This conception of economic complexity focuses on the volume of trade. A more complete description of complexity will also have to consider the network effects of learning associated with production (Root 2013, 239)

[47] Harmonized standards in global trade is not limited to products but also includes services. In the U.S., FASB (the Financial Accounting Standards Board), at the direction of the SEC, has led the transition from US GAAP accounting standards to the International Financial Reporting Standards (IFRS). The IFRS

production scale, potentially at lower unit cost. It also reduces transactions cost of trade by eliminating the customization of standard compliance documentation and certification processes. Harmonization of standards facilitates trade by reducing such costs. The global integration that has occurred is a reflection of the reduction in trade barriers as a result of more closely harmonized standards.

Existing standard-setting organizations quickly responded to increased trade and to the rise of global supply chains by encouraging global adoption of their standards. The international trading system, through GATT, placed significant weight on the importance of reliable standards, which increased demand for global standards. The World Trade Organization (WTO) intensified the use of international standards by encouraging their use whenever feasible.

A second force that contributed to changes in the standards ecosystem is the evolution of the modern firm. First, the international firm (mid-19th to early 20th century) had overseas sales and distribution but most operations were located in the home country. The multinational firm (mid-20th century) created small versions of itself globally and made significant local investments. Finally, the globally integrated firm (21st century)

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began as a system to harmonize financial accounting standards within the European Union, but the value of global harmonization was quickly appreciated (see Chapter 4 in Buthe and Mattli 2013).
In addition to accounting standards, the Bank for International Settlements has coordinated efforts to harmonize capital standards in the banking industry. There are currently three sets of accords, Basel I, Basel 2, and Basel 3. The US and other industrialized countries are in the implementation phase of Basel 3, while developing countries are typically at earlier stages. Most low-income countries are making progress at implementing Basel II, especially when large global financial institutions are present (Gottschalk and Griffith-Jones 2010)

adopts a network structure and locates operations and functions anywhere in the world where they find the right costs, skills, and business environment.[48]

The evolution of the firm has created important management challenges. One significant challenge is how managers respond to the underlying changes in the structure of firms, which now manage and coordinate with more establishments in more countries. Harmonized standards contribute to more efficient management and supervision of internationally distributed production and distribution systems.

The process of globalization has put pressure on the standard-setting system, and the architecture of the current system only loosely resembles the system of a mere 30 years ago. The continual push toward globally integrated markets has reshaped the production of standard-setting activity, especially since the 1980s.

Global Convergence of Standardization I: The Origin of ISO

The research question of this section is concerned with the origin of the International Organization for Standardization. Because the national standards bodies in the major industrialized economies were created only recently, it is worth considering why there was pressure to quickly add an additional standard-setting organization in addition to the International Electrotechnical Commission and the International Telecommunications Union (ITU). Because there were existing organizations, was another international standard-setting organization necessary?

The origin of ISO is intertwined with the other major international standard-setting organizations, ITU and the IEC. ITU, formed in 1865 and 1906 respectively. Both

[48] See IBM (2009, 2).

organizations stemmed from a concerted movement towards international collaboration of standard-setting. These organizations illustrate that standards-setting arose in different ways in different fields, as reactions to practical problems faced in the marketplace. The national and international organizations were created because sector-specific bodies ran into jurisdictional conflicts and needed more coordination.

The ITU and IEC were created to solve specific issues pertaining to their primary industries, although both organizations broadened their purview over time. ITU was created to coordinate the standardization of the telegram industry across national lines, including the standardization of telegram equipment, uniform operating instructions, and common international tariff and accounting rules (ITU 2017).

The IEC was created to coordinate the standardization of prime movers, in addition to associated nomenclature, symbols, and electrical ratings (IEC 2017). ISO was established at a conference that took place October 14-26, 1946. ISO superseded two organizations, the International Federation of the National Standardizing Associations (ISA), and the United Nations Standards Coordinating Committee (UNSCC). ISA was created in 1926, UNSCC in 1944.

The ISA began its first formal meetings in 1928; however, several complications hindered its development. The first problem regarded funding for the organization. The ISA was short-staffed and received only limited engagement from industry, which is a traditional source of funding and one of the principal actors involved in standard-setting.

Another problem was that organizing members could not agree on the appropriate measurement standards to adopt. The Americans and British wanted to adopt their respective standards (U.S. customary units and the imperial system of measure, respectively), while the Europeans, particularly the French, were pushing for adoption of the metric system.[49] Disagreement over these standards doomed the possibility of cooperation, and the Americans and British did not actively participate in ISA's work.[50]

Mr. Heiberg, a founder of the ISA, admitted that the organization "never fulfilled our expectations" and "printed bulletins that never became more than a sheet of paper" (quoted in Latimer 1997, 15). Heiberg did point out that ISA served as a prototype for ISO, which adopted many of ISA's statutes, rules of procedure, and its original technical committees.

ISA's activities ended in 1939 with the outbreak of WWII. ISA president Huber-Ruf closed the secretariat and entrusted stewardship of the organization to Switzerland, where ISA was administered.

ISA was followed by UNSCC, which was founded in 1944 by the U.S. the UK, and Canada to bring the benefits of standardization to the war effort and to the eventual business of reconstruction (Latimer 1997, 16). Membership was initially composed of Britain's former colonies and Allied forces; Axis and the neutral countries were not eligible for membership. The organization was administered in the London office of the IEC by a British engineer named Charles Le Maistre.[51]

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[49] The metric system used by the French at the time was the precursor to "The International System of Units (SI)", which was formally published in 1960. As a small consolation they were able to agree on a inch-millimeter conversion standard (Reck 1956, 38)

[50] BSI standards were also adopted internationally, particularly among Britain's colonies and there was a belief that British standards could be regarded as hallmark enough (Woodward 1972, 48)

[51] Le Maistre was the Secretary of the IEC at the time. He was the founding General Secretary of IEC and had been with the institution since its founding in 1906. He also played a significant role in the meetings that led to the founding of the ISA. His outsize role in standardization has led to him being called "the

The UNSCC was established on a temporary (two-year) basis to focus on coordinating standard-setting activities and to encourage cooperation among its membership; it would not create its own standards (Yates and Murphy 2007; Murphy and Yates 2009). Unfortunately the agency was established too late to be of too much value to the war effort. When the war ended, UNSCC focused on the problems of reconstruction, but discussion turned quickly to establishing a successor organization.

UNSCC initiated the first steps in establishing a successor organization by organizing a meeting in New York in October 1945. That initial meeting was followed by a series of conferences in Paris and London in 1946. The meetings were attended by members of UNSCC's council and representatives from ISA, even though its activities had ended during the war (Coonley 1956). It was decided at these meetings that the best course of action would be to combine the technical work of both ISA and UNSCC and to open membership to all interested countries. The English and the Americans wanted the new organization to be named the "International Standards Coordinating Association," but "coordinating" was opposed by Sweden, among other delegations (Latimer 1997, 20). In the end they agreed upon ISO.

ISO was organized with a general secretariat and a member council. At the time of its founding, ISO had 24 members and 11 council members, although China remained on the council only until 1949; it withdrew from ISO altogether in 1953.[52] At its first meeting two additional members were added, bringing the total to 26. Today ISO has 163

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father of standardization" (Latimer 1997, 16) and the "deux ex machina of international standardization" (Yates and Murphy 2009, 11).

[52] China rejoined ISO in 1978.

members and is globally recognized as the preeminent international standard-setting agency.

Global Convergence of Standardization II: The Success of ISO

ISO soon began its mission to harmonize standards internationally.[53] One way to evaluate ISOs early performance is to examine its role in facilitating and enabling global trade. The increase in trade between countries relates not just to the amount of total tradeable goods but to the complexity arising from denser trade networks. Since 1976, the average number of countries each nation exports to has increased from 20 to 90 (Root 2013, 217). There has been considerable focus on the role of the GATT and WTO as instruments of this new trading network, but there is also a compelling story about the role ISO played in establishing the modern trading system.

The range of work done by ISO was so extensive during its initial years that it is impossible to summarize its accomplishments in just a few pages. BSI identified a dozen product areas, such as steel, ball and roller bearings, and acoustics, where ISO was able to directly facilitate world trade (Woodward 1972, 55–57). Several contributors to the recent collected history of ISO identified its storage container standards (ISO 668 & 1496) as its most important achievement after WWII (Latimer 1997, 35).

The storage container standards were was created through protracted negotiations, which affected multiple stakeholders. They had to manage difficult issues, such as a lack of compatibility among various legacy standards across countries and regions. As an artifact of colonialism, many countries had transportation standards based on British,

[53] Any new institution, as with any new policy, can create unintended consequences or inequality in outcomes. It has been observed that nations with centralized standard-setting bodies have been more successful at the technical committee level in shaping ISO standards (Buthe and Mattli 2013).

French, or Dutch systems (Egyedi 2000). ISO was eventually able to secure agreement on three classes of standards, and the new containers were produced and were available by the mid-1960s (Levinson 2008)

Malcolm McLean, father of the container revolution, estimated that switching to containerized shipping rather than loading loose cargo into the hold of the ship produced savings of approximately 93 percent—a drop in the cost of loading cargo onto an average ship from $5.86 per ton to only $0.16 (Poston 2006).

The containerized shipping box met its initial needs and was successful at reducing the variety of incompatible standards that had prevailed previously. However, it quickly became preferable to create specialized containers for certain purposes, including: refrigeration and insulation; tank containers for (occasionally dangerous) liquids; the ability to accommodate unusual items, such as heavy machinery or oversized pallets; finally a new type of foldable container may reduce costs of shipping or storing empty containers

Fragmentation in the Standard-Setting Ecosystem

The changing structure of technological development that started in the late 1950s with the emergence of computing and advances in telecommunications greatly accelerated in the 1980s. This period saw the introduction and widespread acceptance of the personal computer, the Internet, and rapid innovation in mobile telephony following the breakup of AT&T in 1982. Technological change multiplied the number of potential standard subjects and gradually led to new standard-setting organizations.

The transition to the networked "information age" was accelerated by market reach. The link between market competitiveness and the demand for standards is important. Standard-setting is a distinct characteristic of competitive markets with many participants and relative ease of entry and exit. A feature of an idealized competitive market is homogeneity of product. Standards are important to ensure that products and their parts are indeed homogenous, substitutable, and interchangeable. A monopoly market with no opportunity for competitive entry has no need for externally set standards. The monopolist implicitly sets the standard and changes it at will.

ISO played an important role in the development of Internet protocols during this period. ISO backed the European approach to network architecture, the Open System Interconnection (OSI) project (Russell 2006). An alternative framework was developed by American engineers Robert Kahn and Vinton Cerf through the Defense Advanced Research Projects Agency (DARPA). It appeared that the OSI approach would be dominant because of its widespread support in Europe, however, the effort was deemed too bureaucratic to be workable with the pace of technological change in ICT.

When faced with a tradeoff between efficiency and fairness, ISO has typically sided with the latter criteria in its process of producing new standards (Brunsson and Jacobsson 2002). Even as ISO was gaining prominence for its role in facilitating global trade, frustration with the speed of standardization in ICT led to a period of fragmentation in which the movement toward global convergence of standard-setting activities largely subsided.

The schism in the movement toward global harmonization of standard-setting activities created fragmentation in the standard-setting architecture (Spring 2016), which represented a shift in the entire system structure. The old model was defined by strict hierarchies and a consensus to pursue standardization activities at the highest level in the system when the benefits would be dispersed globally. The rise of consortia created a new model composed of small networks of affected firms. This led to the emergence of new niches, not just at the local level but in the global system. ISO responded to these changes by adopting a different path.

ISO had reached a bifurcation point, which in evolutionary biology is an "irreversible change … that differentiates the evolution of one organism from another. Bifurcation points are minor variations at the beginning that produce large variations at the end" (Root 2013, 237). For ISO the bifurcation point represented a shift in how it approached standardization.

ISO's success in its first 20 years at establishing globally accepted standards, nomenclature, and testing procedures for varied materials led Secretary General Olle Sturen to conclude that the "nuts and bolts" problems of incompatibility were largely gone (quoted in Murphy and Yates 2009, 19). This was a bit premature and self-congratulatory, but it captured the mood at the time. However, by the late 1980s it was becoming clear that, despite its prior success, ISO's role would have to change. Developments in the world economy were rapidly changing ISO's status relative to other standard-setting organizations so rather than relying on what had worked in the past, ISO chose a different path.

Shifting Paradigms: From Compatibility to Global Governance

The process of globalization increased the importance of harmonized standards. The technological change that accompanied tighter market integration facilitated the ability of firms to decouple their production systems from their immediate location. Rather than the Ford model, where the Model T was produced in a giant factory and component-parts manufacturers were local, the production system is now characterized by global value chains with dispersed production. This new decoupling allowed firms to lower costs but increased the burden on management to oversee the process of production. Harmonized standards have been an important part of the globalization story. Of comparable significance to these global standards have been within-firm standards that define and hold together global supply chains. These standards have evolved from quality standards aimed at reducing accidents at munitions factories during WWII to standards focused on the sourcing of raw materials to the marketing of final goods. Standards facilitate procurement contracts between buyers and suppliers, who depend on clear communication of expectations and specifications.

In the late 1980s, ISO introduced a new set of quality management standards. These standards were an important departure for ISO because they were not focused on a product or service but on an organization’s processes. The new standards were also aimed at a new market—business organizations rather than engineers and scientists. These standards were an important departure for ISO because they were not focused on a product or service but on an organization’s processes. The new standards were also aimed at a new market—business organizations rather than engineers and scientists.

In 1987, ISO introduced a new set of standards aimed at the quality of production, which was in sharp contrast to its traditional role in the standardization of physical goods. This was not the first step in a well-developed roadmap but an experimental leap to adopt a new type of standard, albeit one that had been percolating in the background for many years.

The rise of the modern corporate structure, detailed so well by Chandler (Chandler 1977, 1994), led to a desire to rationalize work processes in order to improve productivity (Lampland and Star 2008, 124). The process of rationalizing work found its champion in American mechanical engineer Frederic Winslow Taylor and his seminal *Principles of Scientific Management* (1911).[54] Rather than relying on finding the "right man" for the job, Taylor insisted that the system of production must suitably train the employee: "In the past the man has been first; in the future the system must be first" (1911, 2).

The system Taylor envisioned was based on the rationalization of work processes through "enforced standardization of methods, enforced adoption of the best implements and working conditions, and enforced cooperation" (Taylor 1911 cited in Auerswald 2017, 40–41). Furthermore, "the duty of enforcing the adoption of standards and of enforcing this cooperation rests with the management alone" (Taylor 1911, 64).

The natural outcome of this approach was the creation of a management structure to supervise and train employees and to ensure that they conformed with the system-level

[54] In Europe, Henry Fayol, reached similar conclusions as Taylor and is also credited as a founding figure of scientific management. Fayol was also a proponent of teaching management as a core element of an educational curriculum (Carter 1986, 454).

processes of the new production routines. To supplement scarce management resources, a new class of engineer was created, the industrial engineer. The role of the industrial engineer was to monitor the production system and ensure the successful implementation of the process system through motion and time studies. Improvements to the system would come from management and from these new engineers.

Beyond Taylorism, most accounts of the rise of quality management focus on the influence of two Americans, W. Edwards Deming, who focused on statistical quality control, and Joseph M. Juran, who advocated managing for quality. The common story is that they both became influential in Japan before being more widely accepted in the U.S., although Dr. Deming was influential during World War II and was instrumental in the founding of the American Society for Quality Control (ASQC) in 1946 (see e.g. Walton 1988, 17).[55] But of course the Japanese were not simply receivers of knowledge; they clearly led the way in making the quality revolution and contributed to its intellectual foundations as well as to our modern thinking about lean production systems (Winter 1996).[56] However, the focus on quality management techniques did not occur only in Japan.

Origin of ISO 9000

The impetus for setting a new set of standards has a long history, with early efforts dating back to WWII, when the U.S. and Allied forces experienced quality control problems in many of their munitions factories. Because of the danger involved, the U.S.

[55] ASQC dropped "control" and became the American Society for Quality (ASQ) in 1997 (ASQ 2017)

[56] Deming himself provides an overview of the early history of the origin of quality management in Japan following World War II (Deming 1982). For a broader history of the Japanese focus on quality, particularly at Toyota, see (Kenney and Florida 1993; Womack, Jones, and Roos 2007)

military wanted to ensure the safety of its staff and the safe operation of its facilities. Military procurement regulations were updated so that safety would be paramount, which meant industrial engineers had to rethink the production process. Military standards (MIL-STD) and military specs (MIL-SPEC) were created, which gradually led to creation of the Department of Defense MIL-Q-9858 quality management standard in 1959.

This standard was later adopted, with minor revisions, by NATO and published in the Allied Quality Assurance Publications series of standards in 1969. The NATO standard was later adopted by the UK Ministry of Defense. This version was later developed into the first of three quality management standards at the British Standards Institution (BSI).[57] The first series, the BS 9000 Guidelines for Quality Assurance was developed to address quality problems in the new electronics industry. This was followed by BS 5179 in 1974, the predecessor to the BS 5750 series of quality management standards, which was established in 1979. The final version of BSI 5750:1987 became the first version of the new ISO quality management system (QMS), ISO 9000:1987 (Beaty and Fink 2013). ISO has maintained this family of standards since then. ISO 9000 is unique because it is one of only a few existing quality management systems. Alternative, or supplementary, systems to ISO 9000 include the Toyota production system and Six Sigma, which makes it an important area for study.

The ISO 9000 Series

The ISO quality management standards are actually a set of ISO 9000 series standards that address various aspects of a QMS. They provide guidance for firms

[57] This section draws on (The British Assessment Bureau 2017).

seeking certification that their products and services consistently meet customer's requirements and that their manufacturing process is subject to rigorous quality management standards.

The ISO 9000 family is composed of three principal standards and several supplementary standards that target specialized user groups like accreditors. According to ISO, the primary standards in the 9000 series are:

- ISO 9000:2015—covers the basic concepts and language
- ISO 9001:2015—sets out the requirements of a QMS
- ISO 9004:2009—focuses on how to make a QMS more efficient and effective

ISO 9001 was first published in 1987 and has undergone several important revisions since then. ISO reviews all standards every five years to ensure their continued relevance and the ISO 9000 family has been updated almost every five years; the current iteration, ISO 9000:2015, published in 2015, supersedes the 2008 version. The ISO 9000:2015 covers the basic concepts and language of the QMS.[58] There are several additional standards within the ISO 9000 family that relate to quality management. Firms are formally certified in ISO 9001:2015, which sets out the formal requirements of a QMS. ISO 9004:2009 focuses on ways to make the QMS more efficient and effective, and ISO 19011: 2011 sets out guidelines for conducting internal and external audits of these systems (ISO 2017b). The specific focus of this paper will be the ISO 9001 standards since they are what firms are formally certified in.

[58] This paper focuses only on the existing published standards.

Diffusion of ISO 9000 Standards

The adoption of the ISO 9000 quality management standard series has occurred on a massive global scale. The ISO 9000 standards are diffused across ISO's 163 member countries but certification remains concentrated. The first figure shows the rapid adoption of the standard from 1993 until 2007, a period with double-digit percentage growth (except for 2003, when the certification count declined 11.3 percent).[59] The pace slowed to between 0.6 percent and 8.5 percent after 2007 and included two years of decline in 2011 and 2015 (-6.2 percent and -0.2 percent, respectively).

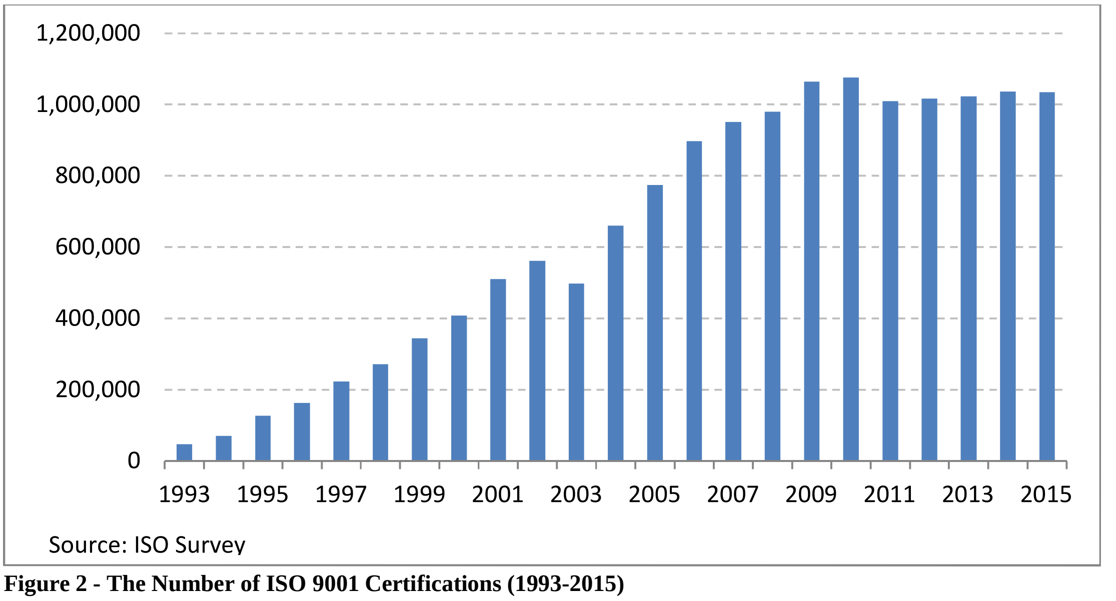

Figure 2 - The Number of ISO 9001 Certifications (1993-2015)

[59] ISO provides data on the number of certifications but does not maintain the data itself. Independent auditing firms verify certification and compliance to the ISO standards and report the data to ISO. These auditing firms are not required to report to ISO, so the data may underreport the total population of certifications. ISO has argued in the past that firms may underreport because they do not want other firms to compete for their clients. ISO made this argument when counts declined during the recession and it is unclear what the true cause of the decline was. There have also been cases of over counting in the data. Finally, although the standard was adopted in 1987, certification counts did not become available until the European Union included the standards in trade directives (Mendel 2001, 81).

The chart below shows how prevalent the standard is in Western Europe and in East Asia, which in part that represents the large size of these economic blocs and the rapid economic growth in certain countries, most notably China, as well as in their large populations. However, it also points to the standard's pattern of concentration and adoption.

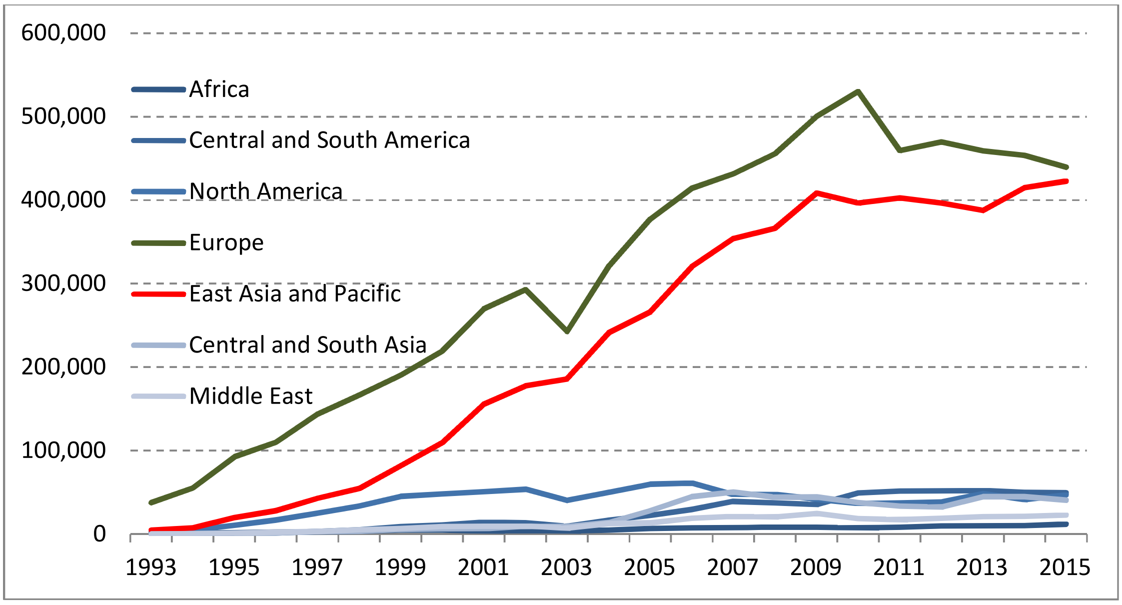

Figure 3 - ISO 9001 Certifications by Region

The table below presents the top ten countries in terms of certified firms, which accounted for more than two-thirds of total certifications in 2015. The data are presented in levels, whereas prior scholarship has reported ISO certifications in a number of alternative specifications: certifications per million peoples (Clougherty and Grajek 2014), certification as a share of total establishments (Blind and Mangelsdorf 2012), and certifications relative to GDP (per $ billion GDP; Mendel 2001). One reason to employ levels is to understand the rapid growth and diffusion of the standards.

There are two notable trends in these data. First, the new quality management standards have expanded globally through distributed networks of production. The fast-growing BRIC nations constitute more than one-third of total certifications: Brazil (#9), China (#1), India (#7), and Russia (#22).

Table 2 - Top 10 Countries by ISO 9001 Certificates, 2015

Rank	Country	ISO 9001 Certifications
1	China	292,559
2	Italy	132,870
3	Germany	52,995
4	Japan	47,101
5	United Kingdom	40,161
6	India	36,305
7	United States of America	33,103
8	Spain	32,730
9	France	27,844
10	Romania	20,524
	Sum	716,192 (69.3%)
	All Others	317,988 (30.7%)
	Total	103,4180

Another striking story is China's share of the total number of certifications. China's share rose from essentially zero in 1993 to 28.2 percent in 2015. This represents the globalization experience very clearly. Indeed, when the certifications are examined by region, it is easy to see how concentrated the adoption has been in Europe and in East Asia and the Pacific. This partly reflects China's rapid GDP growth over this period, as well as its large population. However, India is of a similar size and yet has only one-tenth as many certifications. China's per capita GDP growth has been the fastest in history, however, most of the other countries on this list have higher incomes, which suggests income and population are not sufficient to account for China's share of total certifications.

Management Standards as a New Technology Paradigm

In the evolutionary framework, a selection process preserves the most efficient new variations, which are retained and gradually lead to an industry standard or dominant design (Nelson and Winter 1982; Utterback and Abernathy 1975). The rapid adoption of the ISO 9000 series of standards established the viability of a new class of standards.

With the success and rapid diffusion of the ISO 9000 standards, the ISO leadership realized that they had a powerful instrument that could be applied to other areas, particularly those that had eluded other policy-makers. The next quality management standard marked a sharp departure for ISO but solidified its niche as the creator of management systems in the standardization marketplace.

The success of the ISO 9000 series can also be described as a bifurcation point. By the mid-1990s it was becoming clear that the efforts of the ISO-IEC Joint Technical Committee 1 (JTC-1), which was designed to manage information technology standardization efforts, was not capable of managing technology standards. The JTC-1 was started in 1987, the year ISO first introduced its QMS. The JTC-1 is still active, but it is clear that demand has shifted and that ISO's new standards are primarily the result of its success with the 9000 series.

The new management standards created a new ecosystem, and ISO quickly adapted the standard to create niche markets. Since the general ISO 9000 standards were introduced, they have been adapted for specific industries, including: ISO 29001 for petroleum, petrochemical, and natural gas; ISO/PRF TS 22163 for railway applications; ISO 21001 for educational organizations; and ISO 19443 for the nuclear energy sector. These standards all have the same structure as the ISO 9000 series, including terminology and definitions. In addition to modifying the core standard for specific industries, ISO has found a niche in the government sector. Its QMS has been modified for the management of electoral organizations (ISO/TS 17582:2014), for local government (ISO 18091:2014), and for public water and wastewater services (ISO 24518:2015), among others. Altogether, 78 management system standards were in place by 2017.[60]

Several of the adaptions occurred in response to the rapid adoption of the ISO 9000 series. Shortly after the series was introduction, discussions at ISO shifted to the possibility of introducing management standards focused on enhancing environmental performance. Next to the ISO 9000 series, the best known is the ISO 14000 series, which was designed to help companies and organizations of all sizes manage their environmental responsibilities.

ISO 14000 Series

According to ISO (2017c) the 14000 series:

> "provides practical tools for companies and organizations of all kinds looking to manage their environmental responsibilities.

[60] The full list of Management System Standards is available from ISO: http://isotc.iso.org/livelink/livelink?func=ll&objId=18964860&objAction=Open&nexturl=%2Flivelink%2Flivelink%3Ffunc%3Dll%26objId%3D16474137%26objAction%3Dbrowse%26viewType%3D1 (Accessed July 6, 2017).

ISO 14001:2015 and its supporting standards such as ISO 14006:2011 focus on environmental systems to achieve this. The other standards in the family focus on specific approaches such as audits, communications, labelling and life cycle analysis, as well as environmental challenges such as climate change."

ISO 14000 was introduced in 1996 but data on certifications start in 1999. The number of certificates rose from fewer than 14,000 in 2009 to 337,308 in 2015, but at just over a million certifications, the ISO 9000 is still far more popular. One trend the two series share is the regional concentration. The adoption rate of ISO 14001 accelerated quickly in Europe and East Asia and the Pacific, but it has been much more tepid in the rest of the world. China accounts for 33.9 percent of total certifications, an even stronger concentration than its share of ISO 9000 standards.

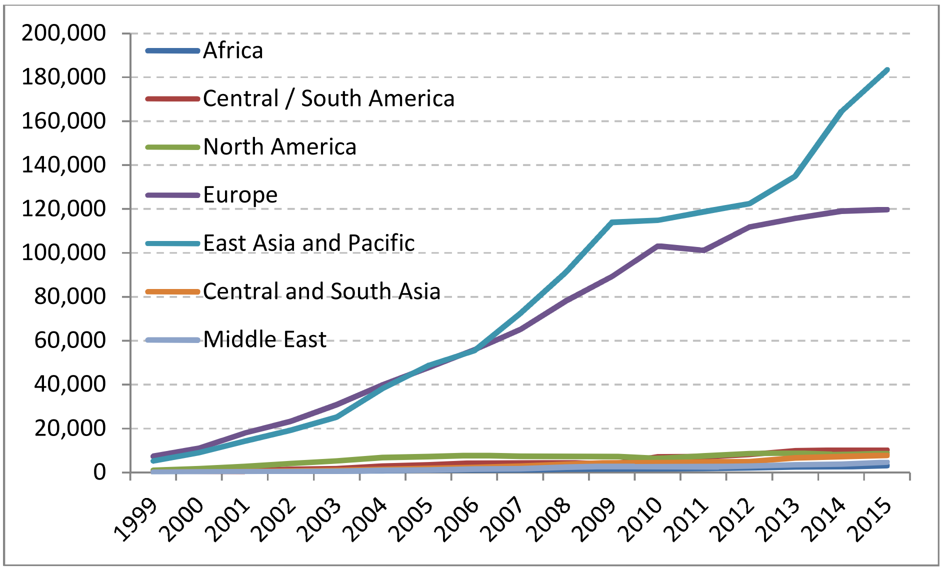

Figure 4 - ISO 14000 Series Certifications

Both of the ISO series were previously BSI standards. BSI introduced its own version of environmental standards five years before ISO, and withdrew its standard once ISO implemented ISO 14000. BSI had become adept at introducing management standards but had largely abandoned its prior practice of creating product standards for UK industry (Tate 2001, 450).

Quality Management Standards and Routines

The final section of this paper examines the relationship between routines and ISO's QMS. Doing so may demarcate differences between codified and tacit knowledge and thus provide some theoretical guidance in understanding the overlap between routines and standards. Herbert Simon (1967, 17) highlighted the importance of codified knowledge:

> In order for knowledge and skills to be transmitted from one generation to another, they have to be stored reliably by memory. Until about five hundred years ago, the two major storage depositories were human memory and man's artifacts. Although writing has been known, of course, for some thousands of years, it was used to only a very limited extent to store the information needed to transmit skills from one generation to the next. One reason, undoubtedly, was the high cost of providing children with the programs (i.e., reading skills) needed to retrieve information from this memory source. A second was lack of knowledge about how to communicate "how-to" information in words generally, and in writing in particular. A third, and the most obvious, was the high cost of producing copies so that the information would be widely available.

An important question left unanswered thus far relates quality management standards to routines. Are these standards a component of routines, are they the same, or is there a different relationship altogether? Agwara et al. (2015) suggest that quality management standards can be viewed as one type of routine instituted by a firm to organize and employ its internal resources and to create the best possible outcomes based on these resources. The link was identified but not fully developed in that paper, and it merits further explication.

One place to start the analysis is by focusing on the overlap in knowledge between routines and QMS. As discussed in the literature review, knowledge is identified as either implicit (tacit) or explicit (codified), two distinct forms that are closely related (Polanyi 1966). Tacit knowledge is generally learned by doing or through research, and it must be written down or otherwise documented in order to be shared and disseminated (Benezech et al. 2001). Tacit knowledge is frequently identified as the main driver of entrepreneurship and innovation, but it cannot be transmitted easily without access to knowledge creators (Polanyi 1966).

The relationship between QMS and routines turns on the question of what type of knowledge can be codified into a standard.[61] There are several challenges in this assessment. First, the literature on organizational routines is conducted by researchers across a range of academic disciplines and the disciplines do not necessarily interact. Scholars in organizational economics typically treat routines as a "black box" of innovation and are concerned primarily with how routines affect firm productivity, whereas organizational theorists outside economics are more interested in the practice of routines, how they operate, and how they are changed when people interact with them (Parmigiani and Howard-Grenville 2011).

In Agwara et al. (2015), my colleagues and I explained that routines can be thought of as algorithms that facilitate business decision-making. An example of an

[61] Codification is a process for expressing, routinizing, and embedding knowledge into infrastructure (Kahin 2004, 59).

algorithm in a traditional computer science setting is a simple if-then statement. If a user types “Hello World” into a programming system, nothing will happen until another line of code executes the request. The specifics vary by programming language, but there is always a trigger and an action. In this case, a command such as “print” will display the terms “Hello World”—the trigger, “print,” implements the action of displaying the term “Hello World.”

In a firm, a production recipe determines how inputs are converted into final outputs, which is an attempt to understand the black box of firm productivity. Inputs to production, which are well analyzed in traditional economic theory, include the labor, capital, and intellectual capital of a firm (Auerswald 2017). The recipe specifies the set of actions that must be carried out in order to transform the inputs into the final product.

Returning to Simon’s point, there are several types of knowledge that must be understood. Lundvall and Johnson (1994) categorized knowledge within a firm four parts: (1) Know-what; (2) Know-why; (3) Know-how; and (4) Know-who. The OECD (1996) popularized their classification scheme in a widely read report on the knowledge economy. The four parts of the framework are:

> **Know-what** refers to knowledge about “facts.” How many people live in New York? What are the ingredients in pancakes? When was the battle of Waterloo? are examples of this kind of knowledge. Here, knowledge is close to what is normally called information—it can be broken down into bits. In some complex areas, experts must have a lot of this kind of knowledge in order to fulfil their jobs. Practitioners of law and medicine belong to this category.
>
> **Know-why** refers to scientific knowledge of the principles and laws of nature. This kind of knowledge underlies technological development and product and process advances in most industries. The production and reproduction of know-why is often organized in specialized organizations, such as research laboratories and universities. To get access to this kind of knowledge, firms have to interact

with these organizations either through recruiting scientifically-trained labor or directly through contacts and joint activities.

Know-how refers to skills or the capability to do something. Businessmen judging market prospects for a new product or a personnel manager selecting and training staff have to use their know-how. The same is true for the skilled worker operating complicated machine tools. Know-how is typically a kind of knowledge developed and kept within the border of an individual firm. One of the most important reasons for the formation of industrial networks is the need for firms to be able to share and combine elements of know-how. This is why "know-who" becomes increasingly important.

Know-who involves information about who knows what and who knows how to do what. It involves the formation of special social relationships which make it possible to get access to experts and use their knowledge efficiently. It is significant in economies where skills are widely dispersed because of a highly developed division of labor among organizations and experts. For the modern manager and organization, it is important to use this kind of knowledge in response to the acceleration in the rate of change. The know-who kind of knowledge is internal to the organization to a higher degree than any other kind of knowledge.

Ludvall and Johnson (1994) classify know-how and know-who as predominately tacit knowledge. Know-what and know-why are closer to market commodities and are more easily codified and disseminated and they therefore are closer in spirit to quality management standards.

The creation of ISO and its role in producing management standards represents an emergent process. The quality management standards were developed at a lower level in the system and percolated up to a higher level. However, the impact of this process also flowed down and affected BSI. Once ISO had adopted these standards the BSI versions were demarcated. This reduced a revenue source for BSI but the organization found a solution by having its charter updated to allow it to conduct certifications. Its role in creating technical standards is now limited but its certification efforts are a global success with local branches in around 100 countries.[62]

This case demonstrates that different levels of the system interact and that the interactions have unintended effects. Some early work on complex systems emphasized the bottom-up nature of change processes through emergence. A more complete understanding of complex systems requires understanding the interaction between top-down and bottom-up change processes and the co-evolutionary nature embedded in change processes (Holland 2014).

Over the 70 years since ISO was founded, it has played a central role in the process of globalization, but has also been reshaped by those same forces. ISO's mission to create the "optimum degree of order" for a given situation affected how it approached its standardization efforts. When ISO was focused primarily on product standards its approach was workable and the slower, deliberative nature of the standard-setting process was not a hindrance. ISO's role in standardizing container s for global shipping has had long-lasting impact and so it was appropriate that ISO took its time to reach consensus and solicit input from a variety of stakeholders.

ISO's experience with Open System Interconnection, by contrast, is often portrayed as a "cautionary tale of over-bureaucratized 'anticipatory standardization.'" (Russell 2013). However, ISO was trying to balance the self-interested recommendations from major computer and telecommunications corporations, state owned telecom

[62] This has been a lucrative business decision for BSI. ISO 9000 certification is expensive. The initial cost of certification has been estimated to start at $10,000 for small firms and to cost hundreds of thousands of dollars for large firms (Tate 2001, 450)

monopolies, and the technical experts from nearly a dozen countries (Russell 2014). ISO's framework for the development of the internet did not materialize, but the TCP/IP standards share many similarities. Nevertheless, the creation of Internet standards switched to a more decentralized approach and marked a shift in the balance of power between ISO and industry consortia that arose to manage the standard-setting process.

ISO was working concurrently on standards for firm production routines. The quality management systems quickly found a dedicated following in Europe and East Asia. The standards represent one of only a few alternative methods of codifying tacit information. ISO successfully adapted to a changing landscape with these new standards, and the creation of the standards created the need for more specialized standards to meet emergent demand.

ISO's pursuit of order has been a constant priority over its existence even as the standard-setting landscape has changed. The forces of globalization, which ISO affected through its product standards, also had feedback effects on ISO. The growing importance of routines in increasingly complex global enterprises created a demand for quality management standards, which ISO was able to supply.

This research on the changing structure of the standardization system raises important questions for future research. One future research agenda should examine the changing institutional structure of standardization activities and how responsive these organizations are to change. There is a tendency for bureaucracy to fulfill internal self-serving business. Regulators may seek to implement more regulations, since that is the tool they have to manage social challenges. Similarly, standard-setting organizations may produce standards at too fast a pace, producing standards that are not necessary, or may produce standards at too slow a pace, thereby hindering economic progress.

Another important research approach should examine how dynamic standards themselves are, or can be. There has been a scarcity of research around this question.[63] The ISO 9000 series has been revised on multiple occasions, as have its supplementary standards. It is important to know what drives or hinders changes in the evolution of standards, what actors encourage revision, and how changes affect stakeholders. The literature on standardization remains under-studied and there still exist important gaps in our knowledge that deserve future attention.

[63] The edited volume, *The Dynamics of Standards* by Egyedi and Blind (2008), is one notable exception.

CONCLUDING DISCUSSION AND SUGGESTIONS FOR FUTURE RESEARCH

This dissertation contributes to our understanding of standard-setting organizations and provides insight into current events. One guideline for the research agenda was to avoid the tendency of some business history narratives (exemplified by Chandler, 1977 but also present elsewhere) to view the present as the final stage in an evolutionary journey and therefore the final stage of a development process (Lamoreaux, Raff, and Temin 2003, 405). The standard-setting ecosystem, as described in this dissertation, has had periods of convergence with increased harmonization, but also periods of fragmentation. Most recently, new entrants have altered the balance of decision-making authority and disrupted the decades-long trend toward global harmonization through organizations like ISO.

Standard-setting organizations have searched for a balance between establishing order and encouraging diversity and variety. There are important tradeoffs regarding the speed of standard-setting, how severely standards limit diversity, and how the process is managed, that merit further exploration.

Since the onset of the second industrial revolution, the standardization process has, at times, emphasized efficiency and speed at the expense of harmonization and consensus. At other times, standard-setting organizations have emphasized harmonization through consensus, even though the desire to arrive at consensus can slow the process of standardization. Standard-setting organizations have shifted priority in response to the underlying pace of technological change, although in doing so the architecture of standard-setting has had to adapt and evolve.

The pace of change since 1990 has been so swift that the traditional standard-setting organizations have had difficulty evolving quickly enough to manage the change. The rise of digital platform economies based on firm-level standards has been more transformative than anticipated. Two-sided markets, such as credit cards, have existed for some time, but the recent shift in digital technology has enabled digital platforms to proliferate. Over roughly the past ten years the Internet has shifted from a period of rapid digitization to a period of data collection and analysis. The standardization efforts around these areas have managed to keep pace, but just barely. There is still little understanding about what an optimal structure and process for standardization looks like in such an environment.

In addition to analyzing how institutional structure evolves, the dissertation explored the value of complexity theory in the study of change processes. Several core ideas were applied to three primary time periods: the second industrial revolution, the period of reconstruction after World War II, and the most recent period, which is sometimes referred to as the third industrial revolution (e.g. Dosi and Galambos 2013). Each time period of this study is associated with a different underlying technology and shifting priorities.

The focus on complexity theory emphasized three broad categories: change processes, diversity, and the link between standardization and knowledge in organizations. Private, consensus-based standard-setting organizations emerged in the late 19th century to manage and bring order to a period defined by rapid change, not just in the economy but in social and political matters as well.

Although the first industrial revolution began in Great Britain, the second industrial revolution was dominated by the United States and Germany. However, Great Britain maintained its central position in the global network of industrialized nations. Inventors in the UK played an important role in the evolution of new technology, for example, and were quicker than their counterparts in creating a national institution to manage standard-setting. The British Standards Institute (BSI) became a model for other countries to follow.

The ascendance of national standard-setting organizations after World War II was the result of ties to the UK, in part the close ties with its current and former colonies. Of note, standard-setting organizations were created in Canada, the United States, Australia, and New Zealand, among others. Proximity and familiarity with BSI were also important, as was the growing realization that standard-setting organizations were necessary but not sufficient to manage the complex matter of setting standards, particularly across industry lines. BSI later helped translate its experience with quality management standards to the ISO, of which it was an active and influential member.

These initial forays into standard-setting were not mapped out or otherwise part of a grand scheme. They instead represented the efforts of thousands of engineers searching for a better position on a fitness landscape; fundamentally it was a process of balancing multiple interests and goals rather than optimizing for each.

Another area where complexity theory improves our understanding of change processes is the study of diversity. Standardization creates tension because it can be a conservative force that impedes progress or it can be a platform on which new innovations are formed. There are many examples of standards having both effects. Standards can produce lock-in on inferior technologies, and they can lead to standards wars. Both are inefficient outcomes. However, there also have been observed cases in which standardization fostered innovation as new standards created niches in response to new demand.

The study of when and how lock-in occurs can be improved by understanding the impact of positive feedback and bifurcation points. At several times in the evolution of standard-setting organizations, participants have pursued one strategy rather than another and led organizations down specific paths. For example, when ISO produced its first quality management standard, it created a new course on the fitness landscape. The success of the ISO 9000 standard created the need for specific versions of the standard tailored to specific industries, and also to new social goals, such as environmental management.

The outlook for the international project of standardization is not as clear as it has been in earlier times. Perhaps there will be a similar consolidation in the creation of standards as the ICT sector matures and consolidates, but for now the supply of standards is dispersed across hundreds of firms and organizations of all types. In the mid-1990s, Carl Cargill (1996, 210) offered his outlook for the three international standard-setting organizations. In his estimation the IEC would manage the ICT transition easily enough because of its specialization in crucial hardware applications, like electrical plugs and switches. That segment of the market has not been subject to the same pressure of rapid change as software. ITU, in his estimation, would have the least success in coming years, although its status in the United Nations does shield it from traditional market tests.

Cargill was skeptical about the future path of ISO, since it was still publishing standards about OSI at the time of his writing, even though the viability of that model had long passed. He was also skeptical about the benefits of ISO's certification schemes. As we have seen, however, ISO has successfully created a niche producing management standards.

The study raises additional questions that should be pursued in future research. The role of ISO's quality management standards is still disputed. These standards might be useful tools for managing knowledge within a firm, or their value might reside in their ability to facilitate trade. Nevertheless, there is a shortage of useful data on standard-setting activities, so this is one potential source that should be explored further.

The ideas of complexity theory improved our understanding of the standard-setting process, but these ideas should also be focused on other institutions and in additional contexts. Finally, as Temin (1981) noted, the second industrial revolution itself is a fruitful subject for study that has largely gone unnoticed. There is much in this era that remains relevant and that could better inform our understanding of current science and technology institutions.

The study of complexity theory and its application to important policy problems is at an early stage. Individual ideas have been applied to analyze specific questions in prior literature, but the wholesale application of these ideas remains in a nascent phase. This dissertation contributes to our understanding of these concepts and brings additional attention to the study of standard-setting organizations, which remains a valuable yet under-studied institution.

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