3 Entrenchment and Scaffolding: An Architecture for a Theory of Cultural Change

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This chapter is about entrenchment and scaffolding, but most of my discussion focuses on these processes in cultural and technological change or evolution. Thus we must begin with a discussion of the elements necessary for an adequate theory of culture and of cultural evolution. This is particularly necessary because, as we argued in Wimsatt and Griesemer (2007), no extant account of cultural evolution casts the net broadly enough to include all necessary elements. Theories tend to be either long on Geertzian "thick description," but described in a way that any kind of scientific account of cultural change would seem to be an offense, or long on biological inspiration and replete with powerful mathematical results (e.g., Boyd and Richerson and work inspired by it) but too thin when it comes to admitting phenomena, processes, and entities (e.g., artifacts) crucial to a theory of cultural change.

After an initial section in which I provide an account of what is required for an adequate theory, I discuss a spectrum of related kinds of entrenchment and discuss other factors that are crucial in describing evolved complex organization. This taxonomy is more detailed and complete than I have attempted so far, and I take particular pains to discuss and characterize the harder and more complex cases in which multiple entrenchment processes may be operating simultaneously (for this is the situation we find in cultural systems) and some of the complications that this engenders. One particular and very powerful kind of entrenchment, "combinatorial entrenchment," in which a number of components are used as a constructional "alphabet" to make a wide variety of adaptive devices or artifacts, is a powerful force for standardization, and has often engendered adaptive radiations, both in biology and culture. I give this process and how a set of elements can come to have this status a more extended treatment. This is done through a more detailed discussion of the emergence of interchangeable and standardized machine parts in the nineteenth century, which was a major factor in midwifing the industrial revolution.

Entrenched features commonly act as scaffolding (though scaffolding is not always entrenched), but in this case we see that the emergence of such a constructional or generative alphabet requires the coevolution of a number of other entities or processes that scaffold it. Such supporting structures and processes seem likely to be universal and necessary features of combinatorial generative systems—a paradigmatic instance of a heterogeneous and distributed hybrid structure as discussed by Griesemer (this volume). Thus the emergence of "armory practice" (for the production of interchangeable parts in muskets) required substantial changes in labor and manufacturing processes, the coevolution of machine tools, and the evolution of gauges and standards, and their use in a way that facilitated the production of parts made to the high standards required for interchangeability. These innovations propagated into other manufacturing sectors and spread a broader methodology of mass manufacture. This example provides a variety of instances of the reticulate complexity that accompanies the emergence of scaffolding in the production of an adaptive radiation of artifacts.

The Architecture of a Theory of Cultural Change

At least five kinds of elements are necessary for a theory of cultural evolution and to account for the role of scaffolding in this articulated structure. These are divided into two main categories.

First there are units of two types recognized in one form or another in all theories of cultural evolution:

1. *Meme-like things* (MLTs) that are transmissible or copyable units. Examples include artifacts, practices, and ideas that are taught, learned, constructed, or imitated. These include both ideational and material things and are themselves capable of being chunked or black-boxed hierarchically. Thus they can engender multiple levels of organization, not all of which are accessible to inspection at a given time. They may be chunked either within an individual's cognition and capabilities or by an organization or profession, which puts together a team of individuals that collectively have the necessary capabilities. There will commonly be populations of such entities showing variation and being targets of differential selection.

Memes have been criticized for being so loosely characterized that almost anything can count. With this looseness, the class of included items becomes so heterogeneous that it becomes difficult, if not impossible, to explicate how they can be reproduced or transmitted. This heterogeneity becomes more manageable when one sees that the MLTs are parts of a complex structure of elements that interact to produce cultural change and that many of these causal structures provide means to or constraints on their transmission, stability, and reliability of reproduction (see also Griesemer, this volume). Positing memes as autonomous self-replicating elements is problematic, as is the common failure to recognize the role of the three kinds of scaffolding elements given as 3, 4, and 5 below (Wimsatt 2010).

2. *Biological individuals* who develop, are socialized, and are trained and acquire skills over time (in multiple contexts or cultural breeding populations) and whose earlier training affects their capabilities, exposure, and receptivity to MLTs or to participation in or interaction with the three classes of elements below. The culturally induced population structures of individuals that mediate the exchange and development of MLTs are generated by the units below and are the main drivers of cultural evolution.

Individuals are socialized through their developmental life histories and make culture through their social and enculturated interactions, particularly in the acquisition, application, and extension of complex skills. These include both the common ones such as becoming socialized, and language use, and also the skills we practice in filling our various differentiated roles. Individuals acquire an array of such skills, which are deployed in various situation-specific combinations in their social and technological interactions, the structure and texture of which characterize culture. Complex group interactions allow the production of entities, artifacts, and practices that individuals could not generate on their own (Theiner, this volume). They develop the capability for cooperative and coordinative interaction and socialization in what become the culturally formed and informed core configurations (Caporael, this volume). Group structure occurs on different size and time scales, sometimes hierarchically organized, sometimes also (in more complex societies) organized in a stable cross-cutting manner. Such groups mediate most of the specialized role differentiation and training that make our society and cultures so reticulate.

Gene–culture coevolution and memetic inspired theories (e.g., Richerson and Boyd 2005) incorporate only some of this structure. Thus the structure arising in development and the order-dependent sequential acquisition of complex skills is ignored in all of the extant theories. Nor is population structure a significant element, past a nod at biological kin- and group selection (a limited use of core configurations) and recognition of the fitness possibilities of trait-group effects. The most significant omissions are culturally induced population structure and its scaffolding effects on training for complex skills, including coordinated tasks with role differentiation, and such things as group identity formation.

These kinds of structure—developmental and populational—fall naturally out of the next three elements, which are required for an adequate theory of culture and cultural change, but left out of existing biologically inspired populational accounts like those of Richerson and Boyd (2005). These are culturally created and scaffolding structures, the built parts of the human cognitive, normative, and affective environment that scaffold acquisition and performance of knowledge and skills and that coordinate their acquisition. Thus an individual's choice of a profession (B. Wimsatt, this volume; Warwick 2003) scaffolds his or her subsequent learning (Li, this volume) and commits the individual to a trajectory of exposure to relevant knowledge and procedures, institutions, and population structures.

3. *Institutions* Institutions are ideational elements like MLTs, but at a social/group level, constituting or containing normative rules or frameworks that guide behavior: social norms of behavior, legal codes, curricula, certification exams, and transition rituals like the bar/bat mitzvah and graduations.

Institutions are the core of Gerson's account of culture,[1] but they do not suffice as a full account of culture and cultural change any more than memes or individuals do. In addition, one needs the following:

4. *Organizations* or self-maintaining groups of individuals, self-organized for some purpose. These are like individuals, but at a social/group level, and include interest groups, firms, nations, and professions. They may undergo development as a function of their size, demography, and histories, and recruit and may reproduce, spinning off other organizations that reflect some of their values, aims, and structure.

These are socially or culturally determined "core configurations" and act as cultural breeding populations to define, maintain, elaborate, and teach knowledge, procedures, and values. Organizations and their interactions play a formative role in generating institutions (Murmann, this volume).

5. *Artifact structures* or artifacts mediating short-term activities or processes (like those found or used in the work environment) or providing physical infrastructure maintained on transgenerational time scales providing "public goods." These may be produced, interacted with, and maintained by the society at large, or they may be infrastructural only for a delimited subgroup—a subculture of practitioners of a specific specialty or users of a specialized technology.

It is tempting to regard this last category only as products of culture or external tools for thought rather than as integral parts of it. However, modern embodied theories of distributed cognition reveal that artifacts and the structured interactions they induce can play such an integral part of cognition of individuals and groups that they must be recognized as elements of culture (Wilson and Clark 2009).

Institutions, organizations, and artifact structures are dimensions or components of a society or culture, and many things we find in culture. Government bodies are hybrids of all three of these more complex entities as are most other complex cultural constructions. I assume that organizations at one level or another are the primary source of institutions, which in turn mediate the behavior of organizations.

An important contrast between biological evolution and cultural evolution enters here: there is only one breeding population for biology since we inherit all of our genes in one bolus. For culture, we are members of multiple overlapping culturally induced reference groups, each a possible source of interaction and learning or transmitting knowledge and practices. We combine information, commitments, and values received from each of these, and selectively relate it to others. Such groups may include professional associations, place of employment, political and governmental affiliations, from local to national, condominium association, religious congregation, various interest groups, each with its characteristic norms of behavior and modes of interaction. And their organization is presumably modulated by the core configurations of various sizes that we find natural.

Many of these kinds of cultural elements are specifically designed to aid the construction or development of and promulgation of competencies and commitments among individuals and organizations. Griesemer and I (Wimsatt and Griesemer 2007) call this *scaffolding*. *Scaffolding* refers to structure-like dynamical interactions with performing individuals that are means through which other structures or competencies are constructed or acquired by individuals or organizations. Material or ideational entities that accomplish this are *scaffolds*. Thus, chaperone molecules scaffold the right configuration for folding proteins (see also Lyon, this volume), and the cell scaffolds gene replication and expression so fully that the cell is arguably the relevant reproductive unit rather than the gene or genome. (Memetics makes an analogous mistake!) So too the enculturated socialized human, whose agency is richly socially and culturally constructed and supported, is also scaffolded.

We must distinguish agent scaffolding, artifact scaffolding, and infrastructural scaffolding, cross-classifying the foregoing types of elements:

6a. *Scaffolding for individuals* Examples of scaffolding for individuals include family structure, schools, curricula, disciplines, professional societies, church, work organization, interest groups, governmental units, laws.

6b. *Scaffolding for organizations* Examples of scaffolding for organizations include articles of incorporation, corporate law, manufacturers' organizations, chambers of commerce, and distribution networks for manufactured parts in the business world.

6c. *Infrastructural scaffolding* A particularly important kind of scaffolding, infrastructure, is so broadly applicable that it may be difficult to specify what particular individuals or organizations and what competencies it is designed for. Language is an obvious one, so obvious it is easily overlooked. Our technological civilization has many such systems: highway, sea, rail, and air networks, shopping centers, containerized shipping, distribution networks for gas, water, power, and telephone, warehouses and reservoirs, public transport, Internet, and waste removal. Since it facilitates so many diverse kinds of things, this kind of scaffolding is commonly very deeply entrenched.

I have not talked explicitly in the preceding six categories about meanings or intentions. They all have their impact through generating or mediating interactions among each other, behavior. So also do meanings or intentions. These are clearly richly implicated in our design and construction of artifacts, in the patterns of our conventions, standards, norms, and institutions, in the acquisition of skills (meaning as use), in spoken and written language as combinatorial generative systems of communication, and a host of other things. Meanings and intentions clearly both drive and emerge from these articulated ideational and material structures and processes. It may be necessary to add explicit treatment of them, and it will in any case be necessary to analyze how they articulate with and emerge from the elements of culture that I have discussed so far. However, this must be deferred for another time.

Various structures and structuring processes characterize the generation and reticulate organization of culture: the reproduction of hybrids from multiple diverse streams, a cross-cutting organization of persons in core configurations, the formative articulations of institutions, and the scaffolding provided by multiple modes of entrenchment will be explored and elaborated in the remaining sections of this chapter.

The Entrenchment Spectrum

Entrenchment is sufficiently important and found in such diverse kinds of systems and situations that it is important to distinguish subspecies of the idea. Entrenchment must also be distinguished from cases of "pseudo-entrenchment" that suggest generative entrenchment but lack the essential characteristic of recurrence. However, in cultural systems, the multiplicity of processes makes it both harder to distinguish and also generates many intermediaries.

1. *Pseudo-entrenchment* Unique historical events versus recurrent descent with similarity.

Entrenchment requires that the action of downstream consequences must *feed back* to maintain the presence of that type of element that is said to be entrenched.[2] Individual events do not get generatively entrenched, even though they may have widespread downstream consequences. Although events with more downstream consequences are more noteworthy than those with fewer, they are not thereby more entrenched. The asteroid collision at the Cretaceous–Tertiary (K-T) boundary 65 million years ago and the invention of the Wright brothers' airplane in 1903 both had major downstream consequences. But once they have occurred, no matter how widespread and important their consequences, they cannot be undone, so there is no question of preserving them or not because of their downstream consequences.

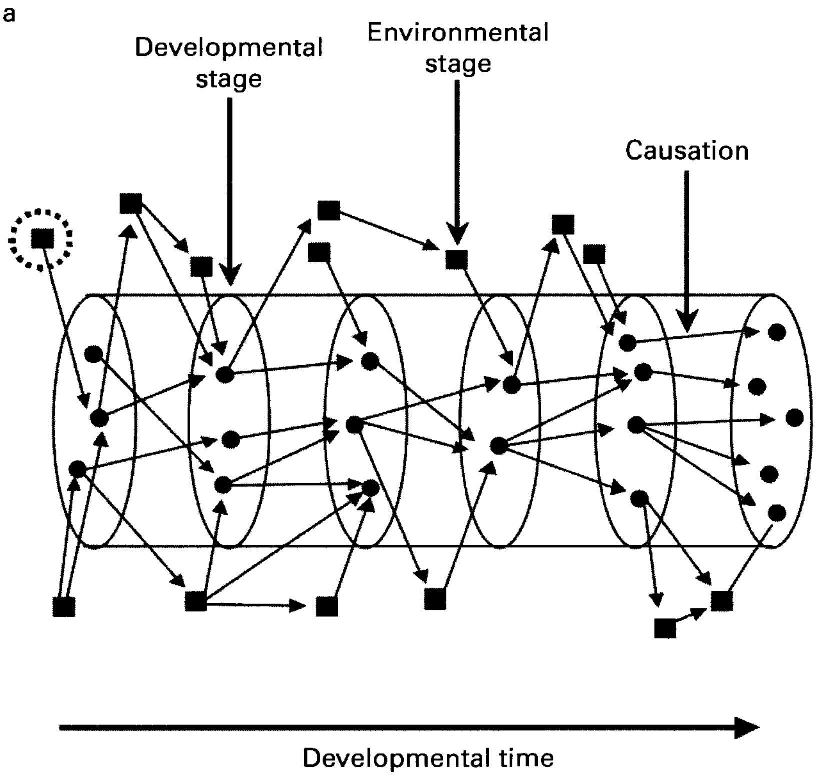
However, their consequences may include new entrenchments because of the changes they have brought about. The K-T mass extinctions of dinosaurs led to an adaptive radiation of mammals, with new entrenchments in many lineages. Some events may be copied or reproduced, or affect processes for reproduction, and when their activity plays a role in their reproduction, generative entrenchment can enter. Processes in development can be particularly tricky. The accident of being raised in a particular family and thus learning a specific language cannot be entrenched although the language can become entrenched in an individual's development through the role it plays in learning more of that language and in the facilitation of other activities, and the patterns of language learning, its early plasticity, and its later fixation in cognitive development can be entrenched, and indeed are, in the human species (see, e.g., Dove 2012).

2. *Simple entrenchment* Our discussion has already led us to this kind of entrenchment, which is the original and main paradigm for entrenchment. Here we have an evolving adaptive system with a recurring developmental trajectory, and differential entrenchment generating different degrees of evolutionary conservation. The more deeply entrenched features are preserved and thus can generate downstream dependent consequences. Paradigmatically, such systems have life cycles and must have some mode of reproduction (sensu Griesemer), either quasi-autonomously, or as part of a larger hybrid system. In this case, generative entrenchment is the reason for preservation of the more deeply entrenched features in the system, and it is called *generative* entrenchment for the role that the entrenched features have in the *generation* of their downstream dependent consequences. (See figure 3.1.)

Consider the construction and influence of the "Wright Flyer" of 1903. The Wrights and other early manufacturers made widespread use of components and modes of construction inspired by and using bicycle components (e.g., their chain drive from engine to propellers and tubular frame construction) that were lightweight and strong. Bicycle technology was widespread (also widely used in early automobiles, where weight and strength were also important). Some design features of the Wright aircraft were copied; many were not. The biplane configuration with an internal combustion engine and pusher propeller were at first widespread (e.g., copied in early Curtiss airplanes, and others until the Moraine–Saulnier tractor monoplane of 1909). The Wright brothers also drew on many design features of their 1902 glider. In some cases the features may have been optimal, but some of them were adopted because they were readily available and worked out or were products of manageable technology.

Of preserved features, the internal combustion engine, and for a while the biplane configuration, became entrenched for heavier-than-air flight. No other power source was strong and light enough, and biplanes provided sufficient wing area and the cross-bracing provided structurally reinforced strength. These became generatively entrenched when their adoption forced a number of other design decisions that depended on them, even though the biplane configuration gave way, after World War I, to desires to reduce air resistance when strength of materials (particularly a change to metal frames and skin) permitted strong monoplane configurations.

Computer hardware and software are unusually rich in compatibility constraints that produce entrenchment. The fear of major system failures emerging when clocks turned over from 1999 to 2000 (the "Y2K" scare) were products of old embedded two-digit date



b

Early change

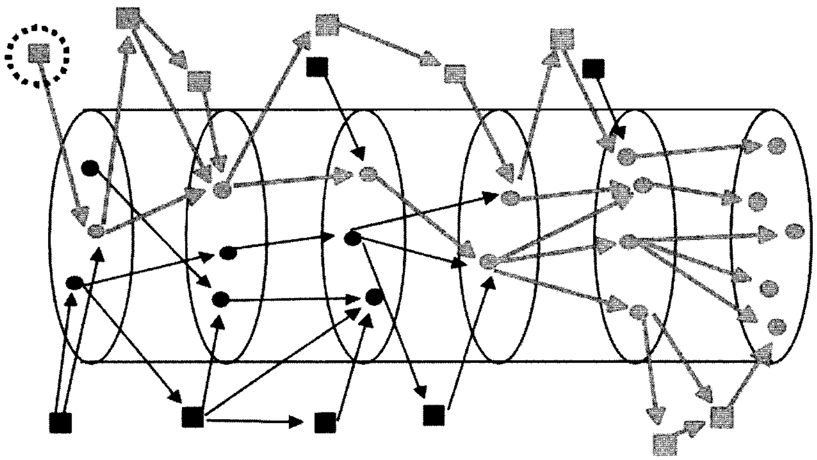


Figure 3.1
Generative entrenchment in a developmental structure (courtesy of Jeffrey Schank). (a) Causal dependency network in an ontogeny. (b) Early change in an ontogeny, with induced downstream changes. From Wimsatt and Schank 2004.

codes that had spread through modern software in the form of older borrowed routines. With them, year 2000 could look like 1900, and financial and other time-dependent records could be compromised. Correcting this required massive reprogramming, and new software and hardware that did not have or depend upon the offending code. The effects of this entrenched scheme were widespread, and its change costly.

The adoption of certain integrated circuit chips in computers generates all sorts of correlative constraints: clock speeds in the chip must be codesigned with bus speeds to manage proper data flow to and from the chip, and "third-party" additions must also conform to this. Word length (initially 4, then 8 in the first round of PC chips, then 16, 32, and now 64 in the latest) must be coordinated with appropriate memory chips and controllers. Bus speeds and specifications undergo a correlative coevolution. Microsoft initially wrote MS-DOS for the 8-bit Intel 8088, and moved to its larger and faster descendants, the 8086, 80186, 80286, 80386, and 80486, for MS-DOS and then the Windows operating system. The Apple Macintosh started with chips of a different architecture, the 16-bit Motorola 68000 (skipping its ancestor, the 8-bit 6802, too slow for the greater speed and processing power required for a bit-mapped screen rather than a character-based system), and Apple's own operating system. Apple went through the 68020, 68030, and 68040 before switching to an IBM chip also made by Motorola. The architectures within these two chip families were highly heritable.

The different basic instruction sets and architectures of the two chip families made for deep incompatibilities between Windows and Macintosh operating systems, programs, file types, and accessories. With each processor and operating system upgrade, consumers of that system and hardware required "backwards compatibility," reflecting the entrenchment of the processor architectures, so that newer versions of software had to be written to run on them and still be able to "read" and operate with the older files.[3] However, this intralineage coherence contrasted strongly with attempts to cross from one system to the other: emulation programs were slow, buggy, and limited. Only after Apple bought Unix-based NexT, on top of which it wrote an entirely new operating system, did they convert to Intel chips (by then with multiple processor cores). This allowed them to run both Windows and Mac operating systems and applications programs on a Mac at comparable speeds (thereby upstaging "Windows-only" computers) but required abandoning software written for the original "Classic" Mac environment. Many Mac owners keep an older Mac to be able to translate older files and, occasionally, to run older programs.[4]

There can also be entrenchment of ideational structures. The development of a theory by an individual can become entrenched when elements of the theory are used to further extend or to apply it, both of which are recurrent iterative processes. This can apply also to a community of adherents of a theory in a group. Elements that are more commonly used will become differentially more entrenched than parts that are not. Parts that are sufficiently entrenched may even become quasi-definitional or quasi-analytic if symbolic, or constitutive or standardized if procedures or instrumentation. Differential use of different elements of the theory, assumptions, procedures, and instruments would predict different responses by different holders of the same theory when it is challenged, as each individual would act to protect those parts of it that have been most useful to them. Elements of theory may become "hard-core"—an unchanging cluster of assumptions that is generative and protected from falsification. This thus generates a phenomenon argued for by Lakatos (1970), the existence of a hard core. However, this stabilization is generated through use, and slightly different sets of these elements may be stabilized for different people. This provides an advance since Lakatos's own account of research programs leaves the question of how things become hard-core unanswered, and the resultant variability of response mysterious. Entrenchment can predict and explain both. This can be seen as a developmental process in the learning and use of a theory by an individual, but it also can be seen in the activity of a community towards a theory or methodology that it uses, and this leads naturally to the next variant of entrenchment.

3. *Maintenance entrenchment* The closed causal loop that explains the persistence of entrenched elements in life cycles can also apply when the elements in question play a role in maintaining an important feature in a persisting adaptive system and thereby contribute to the preservation of the system and itself. These "closed causal loops" give the causal recurrence necessary to explain maintenance of the entrenched elements without invoking the recurrence of successive life cycles. These "system metabolic functions" can play a role in either the operation of stable mature systems or the continued development of competence in a given area or set of areas through continued use or reuse of a developing capability. Thus an ontogeny can generate recurrences and entrenchments within it without passing to the next generation. Language acquisition and the development of mathematical skills, and their continued use within the life of an individual, are obvious examples here, but the development of any sequentially acquired competence in which new skills are layered upon and utilize earlier ones also fits here. The boundedness of these skills within a generation are demonstrated by the lack of heritability of specific languages in cross-cultural adoptions and the lack of any sort of (automatic) heritability of mathematical achievements from parent to child. Nonetheless both language and mathematics can persist transgenerationally in populations of users—language usually spanning the range of a cultural system as a whole, and mathematics (and different parts of it) being taught and used in different subcultures. *This mode of maintenance entrenchment is crucial to identifying entrenchment in cultural systems, where many closed causal loops mediate performance, but systems are persisting rather than reproducing, and biological and cultural entrenchments often articulate on such maintenance entrenchments.*

4. *Factors modulating entrenchment* The causal structure of development and operation of a system can have many modes of organization. In these, local dependencies interact with other organizational modes or factors to produce or modulate a net entrenchment. Primary among these are the following.

4a. *Robustness and canalization* are other ways than entrenchment of producing stability within a system, but they are normally thought of as operating ontogenetically or in a maintenance mode rather than in a phylogeny of repeated life cycles. *Robustness* indicates that a property or regularity is produced for multiple alternative states of a system, so that the system continues to exhibit that property under variations within this range. It is usually thought of as passive. *Canalization* (Tavory, Ginsburg, and Jablonka, this volume) indicates active organization of a system to attain the canalized state over different generative (e.g., genetic) or input (e.g., environmental) conditions—usually by adjusting the values of other variables to bring the system back to the canalized state.

Whereas entrenchment acts through selection to select out alternatives that deviate from the entrenched structure, both robustness and canalization act either to make a range of alternative states selectively neutral or to eliminate deviations through regulatory activity. Three cases should be distinguished:

i. To the extent that a state is robust or canalized, the presence of a particular organizational feature producing it is rendered less essential (because other specific features or the overall structure can do it)—and thus it is less entrenched. *This may free features upstream of that state to change more easily because they are not required.*

ii. And if an element is entrenched, but its production very sensitive to conditions, it would presumably be adaptive to the reproducing system to make changes to canalize it or to make its occurrence more robust. However, if the entrenched state is disturbed early in a developmental life cycle of a reproduced system, it may also be more economical for the reproducing system to abort the embryonic system and start over rather than to rescue it (Wimsatt 2003).

iii. On the other hand, if a state is robust or canalized, its stability makes it a natural target for further entrenchment by other features depending on it for proper functioning (Wimsatt 2003). *This may provide foci for the growth of entrenched structures.*

4b. *Modularity* can figure in two distinct ways in systemic organization that affect entrenchment:

i. Redundancy may occur through duplication of like units. Then individual units become less entrenched although the function realized by the sum of like units may become more so. (Support for redundancy presumably indicates importance of the function served.) Redundancy may also indicate growth in capacity via the production of like units. The presence of ribosomal RNA in multiple copies reflects the need for a higher rate of protein synthesis than possible with a single copy, and massive excess liver capacity (and regenerative capabilities) presumably reflect this also. Here redundancy and entrenchment usually involve required functioning of a specified proportion of units.

ii. Modularity may also arise through the parcellation or differentiation of functions (Wagner and Altenberg 1996). This commonly gives increased efficiency through specialization of the different modular elements as the system increases in size. Cellular differentiation of initially like cells is the prime example here, as would be the role differentiation of individuals to different occupations in a complex society. Here the different functions served tend to become increasingly entrenched. However, if a system of given complexity becomes segregated into modular subunits with lower interaction between them, the lower interaction between units would tend to decrease their entrenchment.

iii. Modularity can emerge through the development of a combinatorial system, whose elements then become modules that can function in a variety of different contexts. This is sufficiently important that I take it up below as a separate kind of entrenchment and develop examples arising from it throughout most of the rest of the chapter.

5. *Combinatorial entrenchments* One of the most striking and fruitful modes of entrenchment is combinatorial entrenchment. Combinatorial systems are adaptations of larger systems that provide a systematic way of generating a large number of variations arising out of elements that can be put together in different combinations in multiple ways. These elements thus become modules, which can play the same or different functional roles in the different systems they are used in. Thus nuts and bolts are made in multiple sizes for multiple uses, as are electric motors of varying voltages and power capacities. The combinations provide readily generated possible alternatives from which complex structures can be assembled to accomplish a number of tasks. These combinatorial possibilities make the elements increasingly entrenched as they come to be used for diverse functions in a variety of different constructions. This allows the rapid evolution—usually in an "adaptive radiation"—of the systems containing the combinatorial systems.

As the basic parts combined become widely used, they become "standardized," even universal, elements of constructing more complex systems, as the genetic code and proteins have been. Because they must be put together with other elements, this often requires that they meet more demanding tolerances, rejecting variability that would have earlier been tolerated. They may also be combinable only in limited ways, imposing a "syntax." And among those syntactically possible combinations there may be other constraints of a more adaptive nature for which combinations are useful. This process can be iterated: if these combinations can themselves be combinatorially assembled (leading to hierarchical chunking) new constraints may emerge at the higher level. In some cases, these higher-level combinatorial elements may be assembled into systems for volume or "mass" production.

In a combinatorial system, standardized parts become polyfunctional, usable in different ways to accomplish different roles (see table 3.1). And there may be combinatorial takeovers through growth of the combinatorially composed systems over alternatives satisfying the same function:

Table 3.1
Polyfunctional nut–bolt combination

Function	Nut–Bolt Implementation
Fixed connection	Structural rigid connector (plus lock washer)
Shear pin (designed to fail before other more costly structural elements)	Structural rigid connector (plus lock washer)
Fixed spacer	(with collars or washers)
Connection fixed in one dimension, free in another	Allow free rotate (shaft) between fixed clearances
Continuously adjustable connection	Adjust travel (screw adjusts length, to clamp as in a vise) To raise or force apart as in a jack; high force, high mechanical advantage
Integral part of larger mechanism	Measuring device (micrometer, with calibration, ruling) "Rheostat" voltage control
Complex (multiples)	Levelers on legs of supported structure (with "shoe")

Note. Common (especially standardized) elements can become widely used for diverse functions. (If standardized—e.g., for thread count and depth for shaft size—these can generate strong constraints on structure of elements interacting with them.) Here we consider a nut–bolt pair, with threaded shaft and hole.

1. by adaptive radiation (adaptability breeds diversity),
2. by outproduction and market forces (rapid assembly, lower cost, scale economies),
3. and for technology, by conversion of other architectures (through translation, reverse engineering, motivated imitation).

Many such systems exist, both for biology and for culture. They are perhaps the most important kinds of evolutionary innovations. The origin of the biological systems (such as the genetic code) are sufficiently old not to be readily accessible, but the consequences of the existence of such systems are of foundational importance.

Examples of such systems in *biology*:

1. The four nucleic acids comprising alternative sequences in DNA molecules.
2. The "genetic code," mapping triplets of nucleic acid sequences to a 20 + 3 set of 20 amino acids and stop codons, going in strings of amino acids to compose the primary structure of proteins. This mapping is redundant since $4^3 = 64$ possible triplets maps to 21 states, generating a kind of coding robustness for some of the amino acids.
3. The roughly 20 "dynamic programming modules" (Newman in press) or "signaling pathways" (Gerhart in press) performing different operations in metazoan cell aggregation and differentiation allowing a variety of different kinds of cell assemblages.
4. The combinatorial antibodies produced by the variable parts of the RNA sequences in the adaptive immune system of vertebrates that allow us to "fit" or "recognize" arbitrary foreign protein antigens and to generate an immune response to them.

With more degrees of freedom, *culture* can generate variational systems more easily, and their relatively recent origins are often more accessible:

1. Words and syntax for their combination in spoken languages.
2. Iconic writing language systems (in which the written symbols can be widely diffused without the presence of the speaker and can persist for multiple generations).
3. Phonemic and then alphabetic language systems which could transliterate other languages phonetically and require learning a much smaller number of basic signs.
4. Standardized machine parts that can be used to make diverse machines (and complemented by "design alphabets" as in Herkimer's *Engineer's Illustrated Thesaurus*, discussed below).
5. Standardized electronic parts that can similarly be used to make a variety of different electronic circuits.
6. Computer languages with standardized instructions that can be used to write diverse programs (of which particularly useful parts may later become embedded as reusable components in libraries of routines).
7. Diverse modes of professional training to produce individuals capable of playing standardized roles (draftpersons, toolmakers, electricians) in larger units, such as manufacturing firms.

Combinatorial modules can also be used in mass-production systems:

1. Multiple copies of ribosomal RNA and multiple ribosomes in the endoplasmic reticulum increase rate of protein synthesis through parallel processing.
2. Reproduction and differentiation of cells make larger diverse specialized organs in complex metazoans.
3. Printing with movable type (can compose and make multiple copies of arbitrary text).
4. Interchangeable parts for mass production and repair.
5. Standardized parts (and organized sequences of machine tools to make them) in order to make a variety of possible machines out of the same basic parts.

I return below to a historical discussion of the nineteenth-century evolution of standardized parts and machine tools, which also involve correlative scaffolding changes in the nature of labor and the character of production. These show nicely the interaction of the five types of elements I characterized as necessary to a theory of cultural change in a rich network of scaffolding relations.

6. *Overlapping and embedded entrenchments* A complex compositional structure may involve many different-sized and hierarchically composed systems reproducing on different time scales. This occurs in biological and cultural systems and in hybrids of both.

Metazoans develop through multiplication and division of cells, so entrenchment in cellular processes and reproduction through mitosis is embedded in metazoan development. Animal husbandry and selective breeding of domesticated animals is a historically important hybrid involving entrenchments in animal life cycles and entrenchments in human cultural practices. Entrenchments occur on the time scale of individual ontogenies, both in biology and in cognitive development. Factors said to be "innate" in individual cognition commonly arise through entrenchment in cognitive development in human evolution (Wimsatt 1986, 2003) but may enter into helping to form the acquisition of language (Dove 2012) or other cultural processes in the individual (Heintz, this volume). These enter into training processes for acquiring complex sequential skills as new employees learn their specialized tasks in a corporation. Within ontogenies of individuals, cycles of repetitive learning entrench individual practices and quirks within habits. Habits are layered, with earlier entrenched habits modulated and entrained in later modulations employing them. Increasingly high-level cognitive activities may become chunked until such arcane skills as differentiating a function may become almost automatic. Within our culture, cognition is intertwined with various modes of material and cognitive scaffolding (Wilson and Clark 2009), from apprenticeship (Sterelny 2012, B. Wimsatt this volume) to writing and numerical computations with pencil and paper, to complex cognitive–motor tasks with material tools, up through programming and the use of sophisticated software. The organizations we participate in have their own entrenched practices and processes scaffolding their activities: anyone who has worked for IBM leaves the firm a "Big Blue" person to some extent, even down to the practice of wearing three-piece suits, deriving from the decision of IBM to have their sales force "go native" in their interactions with bankers.[5] The demography of enskillment, knowledge, and technology in a corporation may affect and direct how it responds to emerging markets and technological developments (Henderson and Clark 1990). Such systems will thus involve multiple overlapping entrenchment processes, with embedded entrenchments amplified or modulated by higher-level entrenchments.

7. *Evolutionary meta-ontogenies* With overlapping entrenchments of lineages with possibly different length life cycles and scopes, the emergence of hybrid lineages formed by multiple converging or interacting lineages that are difficult to classify in traditional categories for evolving systems

1. may show definite ontogenetic features, but
2. may, unlike organisms, not have determinate life cycles or determinate ways of reproduction (e.g., business firms[6]),
3. may evolve (possibly without a demic populational environment of exchange or competition), and
4. may show substantial horizontal borrowing or lateral hereditary transmission compromising the individuality of the lineages, and

5. may be strongly interactive with other like entities—so strongly that separations may seem arbitrary or delimitable in multiple possible ways, so that it is problematic to individuate species.

As a result of the ambiguities in this list, it is often hard to decide whether such systems should be described as developing or evolving—a problem noted in Gerson's contribution to this volume, as in other critiques of cultural evolution (Fraccia and Lewontin 2002). This is not a serious problem and is clearly explicable and unproblematic on this analysis. Possible examples of this category would include local ecosystems composed of interacting demes of diverse species, which might undergo the processes of "maturation," as in ecological succession;[7] business firms which grow and recruit and train human individuals who acquire seniority in the corporation while the market for the products produced, and the age-structure and training of the employees changes, modulating how the firm can respond to new market forces and technological developments. In this, populational units (individuals, ideas, artifacts, firms) undergo cultural evolutionary change, but the overall character is of coevolutionary change (Murmann, this volume; Wimsatt and Griesemer 2007) in something more like an ecosystem with rich interpenetration and interdependency of the various lineages.

The development of our technological culture as a whole may constitute a single richly interactive system that is too strongly connected to be separable, in part due to the multiplicity of physical phenomena harnessed in even relatively small technological parts, and the diverse supply sources involved in the production of any complex technology today, compounded by the diversity of technologies used together in our everyday activities. There may be other major cultural units that interact more weakly with technology (religious systems might have seemed possible—at least until religion became politicized in the last decade), though others (such as government, economics, education, and the monetary system) seem too richly connected to be readily separable. What emerges is like an immense ecosystem of culture.

However, through all of this generative entrenchment shows its particular advantage: one can follow and evaluate generative entrenchment relations wherever they may lead. We don't need populations of separate individuals or isolatable species. The distinction between intrasystemic and extrasystemic effects is of no particular moment because of the multiplicity of hybrid systems. If something has many downstream effects, the chance of major problems if it is seriously perturbed becomes a source of resistance to change. Thus generative entrenchment should be a particularly useful tool of analysis for complex systems with multiple overlapping entrenchments and in hybrid systems constituting evolutionary meta-ontogenies. These hybridities have made heredity almost impossibly complex for cultural systems (Wimsatt 1999, 2010), and delineating developments may be hard when it is hard to individuate entities or lineages, but it should be relatively easy (though far from trivial) to trace dependencies within these complex entities.

Adaptations to Allow or Facilitate Deep Modification

A crucial general feature of "escape mechanisms" allowing deep modifications in an entrenched structure is to find ways to allow changes to preserve rough functional equivalence for the entrenched feature or continued performance of function while it is modified. This is a situation that commonly requires scaffolding. Three different and important examples in biology—tandem duplication, functional redundancy, and robustness—each provide ways to make allowable substitutions through preservation of the relevant functional role (A. Wagner 2006; Wimsatt 2012). This mode of escape is very important, because the change to another structure that preserves functional role in relevant respects may allow new exaptive evolution in other dimensions. Culture has generated multiple strategies for facilitating such swapping. Manufacture of technological artifacts allows for easier deep modifications because we can treat components as nearly decomposable and "pull them out of context" to make modifications on internal architecture or processing and then reinstall the redesigned component, which need only interface with the embedding system in a manner preserving functional equivalence. (Thus the "engine swapping" so popular among "hot rod" enthusiasts in the '50s.) Object-oriented programming has deliberately designed a syntax for the creation of objects that are readily modified and reused, either within descendants of the program they appear in or borrowed for use elsewhere. This (and many other heuristics usable in our artifacts) is not possible, or is so only in a more attenuated form, with biological systems. (This is discussed more fully in Wimsatt and Griesemer 2007.)

A Case Study of Combinatorial Entrenchment: The Emergence of Standardized Parts and Machine Tools

Many diverse and complementary combinatorial systems are characteristic of culture. The origins of spoken language are largely unknown, but obviously crucial to the development of coordinated behavior among early hominids, and had word modules that could be combined in structured ways from a time estimated (from divergence of known languages) as going back something like 50,000 years. Written language went rapidly through a number of stages from its origin in the Middle East.[8] Bookkeeping counters for agricultural produce go back to 8000 B.C., but full-fledged written language dates from about 3500 B.C. The language was originally iconic (like Egyptian heiroglyphics), but about 1600 B.C. phonetic variants appeared (giving the ability to transcribe other languages by creating words to match their sounds), and by 1200 B.C., alphabetic languages emerged. In this manner word modules gave way to phonetic sound modules, and then to standardized ways of spelling them composed of still smaller symbolic elements. In writing, the use of a stylus in cuneiform writing used standardized strokes to make the diverse alphabetic letters, using even smaller modules combinatorially (Woods 2010). The use and number of functions served by written language grew as the writing systems developed, from storage of records, contracts, histories, and literature, to the extended support for cognition that it provides today.

The manufacture of standardized parts and mass production are closer to the present, in the nineteenth century, well documented, and provide a fascinating example of the emergence of a combinatorial system that was crucial to the development of the industrial revolution. It is also sufficiently extended to allow discrimination of multiple stages in its emergence. The first motivation leading in the direction of standardized parts was the desire of the military for muskets with interchangeable parts. Although given an economic gloss, such arms were initially more expensive (because of the new machinery and setup costs required for their production), and the main motivation was to reduce the number of arms put out of action and allow for much simpler repairs in the field—something crucial to an army and worth the added expense. Starting in 1812 the Ordnance Department of the new American government encouraged development of interchangeable parts in arms produced at each of its two armories in Springfield, Massachusetts, and Harper's Ferry, Virginia. Interchangeability was not easy and not fully achieved until 1841, when percussion muskets produced at the two armories had parts interchangeable not only with muskets at the same armory but with each other (Smith 1977). A British inspection committee visited the arms factories, and also other industries in 1854, to learn the early stages of the "American system of manufacture" and brought these methodologies to Europe.

Why did it take so long? Several developments were required before interchangeability was achieved. Manufacturing procedures required reconfiguring the workforce and mode of production, but also the development of specialized machine tools, and of gauges for accurate dimensioning, and frequent measurement operations to make parts to given standards with successively greater precision. A move away from the craftsman tradition of individuals who made whole rifles to separately decomposed tasks of making individual types of interchangeable parts required changing other labor practices: demands that people keep regular hours and specialize on simpler subassemblies (like "lock, stock, and barrel"), and later on the work path was decomposed further to have individuals concentrate on still smaller parts or operations on them. Less skilled or unskilled workers replaced craftsmen (who were in short supply) and were paid lower wages using piece rates. These were all innovations, and most met with resistance from workers as their jobs were "de-skilled" (Smith 1977).

The Harpers Ferry and especially the Springfield armories were production centers in two other respects (Hounshell 1984). A number of "mechanics" learned the emerging mass-production techniques in these and in other smaller centers of arms manufacture and fanned out to other industries that began to take on "armory practice." Secondly, the elaborate development and use of specialized machine tools allowed precision operations, and their configuration in a set order (to avoid time loss and errors in resetting for different operations) allowed workpieces to be passed from one to another for successive operations.

All of these (with frequent inspection operations) contributed to the reproducible production of parts sufficiently similar to be interchangeable. The use of these machine tools (originally designed by specialist armorers developing these methods, like John Hall) spawned a machine tool industry that made both tools specialized for other ends and tools which were adjustable to diverse operations. The Ames Manufacturing company and the American Machine Works were both founded in the 1830s in Springfield, Massachusetts, and made and sold a variety of kinds of machine tools to other American manufacturers and to European governments (Smith 1977, 288).

The use of gauges and measurement is a third factor that deserves special mention (Hounshell 1984, 41–42). Hall adopted the use of three sets (each comprising 63 gauges) for the first variety of muskets successfully produced with interchangeable parts. There was a master set against which all others were calibrated, an inspection set used for testing whether the pieces met the standard, and one or more work sets, used for testing in the actual production of the pieces. This allowed for successively reduced wear on the inspection and master sets. (Similarly, DNA as the master molecule produces messenger RNA as the "working" molecule in protein synthesis, while proteins do the work.) Another important innovation by Hall was to set up a system for measuring all dimensions in the assembled product from a single reference or bearing point, so that error or "slop" in the placement of various fixtures to do operations on the whole piece would not be cumulative. (Similar principles were later used in constructing accurate "linkage maps" of the location of factors in chromosomes [Wimsatt 1992]). But practice was still required: the desired interchangability required a learning and ongoing feedback process of redesign involving back-and-forth interaction between machinists, machines, and inspection procedures.

These methods spread to other industries that included sewing machines and woodworking, McCormick reapers, and finally to full and mass production with the emerging bicycle industry in the 1890s. None of these managed full interchangeability immediately—thus it took Singer from the 1850s until the late 1880s to achieve that (Hounshell 1984). Interchangeability was a function not only of precision in parts manufacture but also of the demands of assembly and materials, and the latter escalating demands were often driven by an escalating technology. Thus it was easier to generate interchangeable rungs for wooden chairs than it was for metal screw threads that had to interface with complementary threaded holes on a "mating" piece. Standards of precision and demands on materials grew as automotive and later aircraft production emerged and rendered the manufacturing and inspection process ever more demanding and complex (Stoff 1993). As the number of types of parts and technologies has grown, the number of design constraints and standards has grown commensurately.[9]

Other kinds of events mark the way to increasing standardization and entrenchment. When a part becomes sufficiently standardized, there emerge in effect obligatory functional norms on how it can be made. To fail to establish such norms is technologically and commercially lethal, as the part is basically unusable in the extant technology. (This is a species of sometimes very demanding coordination game.) When one technology is not universal, the different technologies can be literally incommensurable. I have already discussed Intel and Motorola integrated circuit families and Windows and Macintosh operating systems and software. Although there are kinds of software that run on both systems, neither of the specific programs with the same name (e.g., Microsoft WORD for Windows, vs. Microsoft WORD for Mac) will run on the other kind of computer—they are merely designed to have the same "look and feel," although the operating system intervenes to prevent this from being total, as any user of Microsoft Office on one machine or the other can verify. Older incompatibilities include electrical voltages (and DC or AC current), different style electric plugs in different countries, and English versus metric threads and size-dependent fixed tools (like wrenches). Culturally, of course, language differences are perhaps the deepest kind of incommensurability, and formal languages are much less tolerant of variance in definitions than human language. As a result, different definitions of key terms generate incommensurability among massive genetic databases, and major efforts are under way to set communal standards (Leonelli 2011).

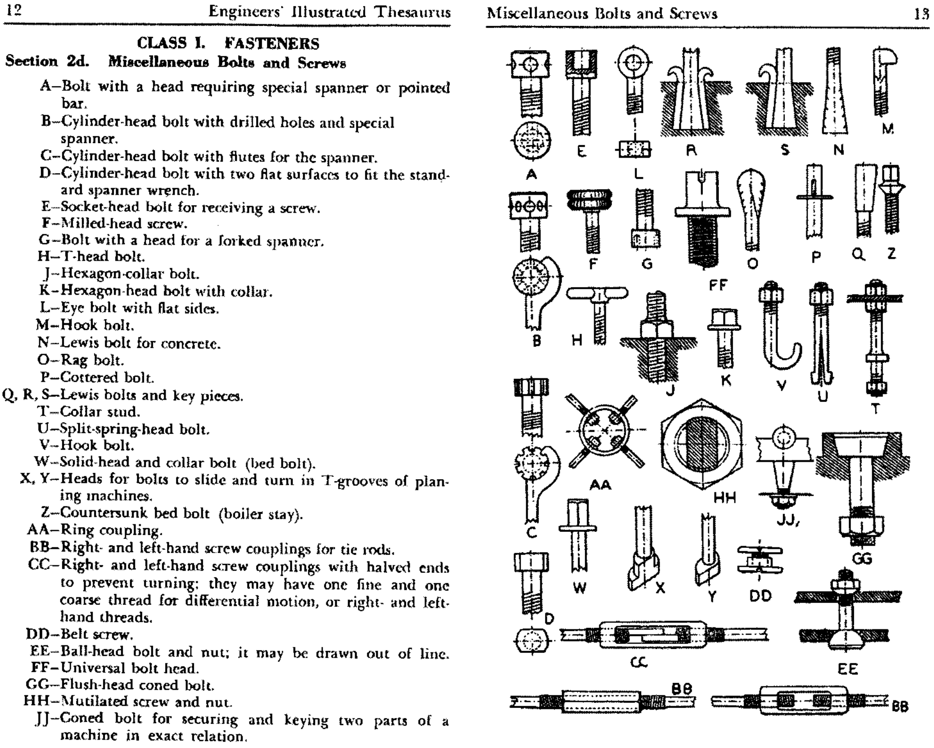
Scaffolding appeared throughout this process: changes in the size and organization of tasks and the organization and character of labor; new norms affecting labor behavior mediating the coordination necessary for factory work; the development and use of gauges and standards; the emergence of a machine tool industry; the appearance of subcontracting and the distribution of materials and parts, and the character of the products. These have changed our lives—both as labor and as consumers—in multiple ways and the products that emerge from this manufacturing process.

I summarize the major steps in standardization and deep entrenchment that occur after parts first become interchangeable:

1. Different part families or configurations compete, until one achieves enough market dominance to compel choice of it as a "standard."

2. Parts become standardized (across manufacturers, with coordinated sets of standards, often designed by a joint committee). If widely adopted, the standard becomes self-reinforcing—a coordination game. Machine tools and gauges are crucial here to ensure uniformity, and standards are often supported by conformity assessment programs by engineering or manufacturers associations.

3. To become truly universal, either the parts are manufactured and incorporated only in a few places (as would be true for basic computer components), or else they need to be distributed if they are going to be used or assembled more widely. Thus we have specialized hardware, electronics, plumbing, and auto parts stores and a legion of more specialized suppliers (such as for scientific equipment—see Wimsatt and Griesemer 2007) to distribute and assemble equipment that meet the mutual constraints necessary to work together. The need of getting the right parts to the right place at the right time has



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CLASS I. FASTENERS

Section 2d. Miscellaneous Bolts and Screws

A–Bolt with a head requiring special spanner or pointed bar.
B–Cylinder-head bolt with drilled holes and special spanner.
C–Cylinder-head bolt with flutes for the spanner.
D–Cylinder-head bolt with two flat surfaces to fit the standard spanner wrench.
E–Socket-head bolt for receiving a screw.
F–Milled-head screw.
G–Bolt with a head for a forked spanner.
H–T-head bolt.
J–Hexagon-collar bolt.
K–Hexagon-head bolt with collar.
L–Eye bolt with flat sides.
M–Hook bolt.
N–Lewis bolt for concrete.
O–Rag bolt.
P–Cottered bolt.
Q, R, S–Lewis bolts and key pieces.
T–Collar stud.
U–Split-spring-head bolt.
V–Hook bolt.
W–Solid-head and collar bolt (bed bolt).
X, Y–Heads for bolts to slide and turn in T-grooves of planing machines.
Z–Countersunk bed bolt (boiler stay).
AA–Ring coupling.
BB–Right- and left-hand screw couplings for tie rods.
CC–Right- and left-hand screw couplings with halved ends to prevent turning; they may have one fine and one coarse thread for differential motion, or right- and left-hand threads.
DD–Belt screw.
EE–Ball-head bolt and nut; it may be drawn out of line.
FF–Universal bolt head.
GG–Flush-head coned bolt.
HH–Mutilated screw and nut.
JJ–Coned bolt for securing and keying two parts of a machine in exact relation.

Miscellaneous Bolts and Screws 13

Figure 3.2
Herkimer's *Engineer's Illustrated Thesaurus*, pp. 12–13. Threaded fasteners.

supported a host of other innovations, most particularly computer-supported just-in-time ordering and containerized shipping (Levinson 2006), which facilitated each others' development. There are in effect the circulation and metabolic systems of the economy.

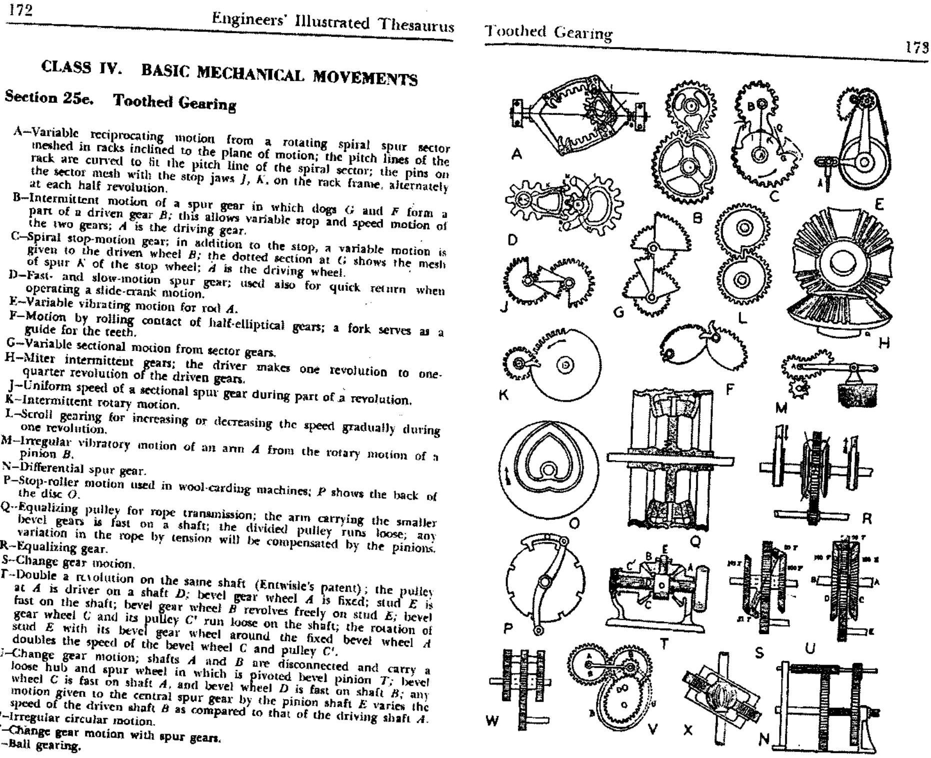
4. Parts become more polyfunctional and generatively entrenched (see table 3.1).

4.1. Different varieties of parts for different specialized applications arise, all modulations of the same basic design, as illustrated with threaded fasteners in figure 3.2.

4.2. The aspects that are standardized become categorical (metric and English threads are incompatible), barring use of replacement parts or tools designed for one on the other. Now generatively entrenched, they become narrowly specialized (and replaceable only wholesale) or broadly applied and virtually irreplaceable.

4.3. With innovations, where one artifact replaces another, if standard formats affect compatibility, "backwards compatibility" becomes an issue and reflects entrenchment. (Can you still read old file formats with your word processor?)

5. Design becomes systematized. This is in part through institution of engineering curricula, but also through institution of common reference standards. Herkimer's (1952) remarkable text is one such example. It is a "thesaurus" of mechanisms, and worthy of special note (see figures 3.2 and 3.3). It serves to systematize design practice, and to modularize the design process, breaking the problem of generating a complex design into simpler subproblems.[10] This 572-page "thesaurus" is organized by function and within function by kind of mechanism, each page with multiple mechanisms using the same basic design principles. It creates a "design language" of alternatives. Here an alphabet of ideas is created. These are types, not particular parts, and must be adapted in detail for the specific mechanical system being designed. They aren't strict functional equivalents since each is specialized to a more particular kind of application. This text encourages engineers to break complex design problems into subproblems (Simon's [1962] "near-decomposability") and to use existing solutions rather than to invent yet other variants



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Toothed Gearing 173

CLASS IV. BASIC MECHANICAL MOVEMENTS

Section 25e. Toothed Gearing

A–Variable reciprocating motion from a rotating spiral spur sector meshed in racks inclined to the plane of motion; the pitch lines of the rack are curved to fit the pitch line of the spiral sector; the pins on the sector mesh with the stop jaws *J*, *K*, on the rack frame, alternately at each half revolution.

B–Intermittent motion of a spur gear in which dogs *G* and *F* form a part of a driven gear *B*; this allows variable stop and speed motion of the two gears; *A* is the driving gear.

C–Spiral stop-motion gear; in addition to the stop, a variable motion is given to the driven wheel *B*; the dotted section at *G* shows the mesh of spur *K* of the stop wheel; *A* is the driving wheel.

D–Fast- and slow-motion spur gear; used also for quick return when operating a slide-crank motion.

E–Variable vibrating motion for rod *A*.

F–Motion by rolling contact of half-elliptical gears; a fork serves as a guide for the teeth.

G–Variable sectional motion from sector gears.

H–Miter intermittent gears; the driver makes one revolution to one-quarter revolution of the driven gears.

J–Uniform speed of a sectional spur gear during part of a revolution.

K–Intermittent rotary motion.

L–Scroll gearing for increasing or decreasing the speed gradually during one revolution.

M–Irregular vibratory motion of an arm *A* from the rotary motion of a pinion *B*.

N–Differential spur gear.

O, P–Stop-roller motion used in wool-carding machines; *P* shows the back of the disc *O*.

Q–Equalizing pulley for rope transmission; the arm carrying the smaller bevel gears is fast on a shaft; the divided pulley runs loose; any variation in the rope by tension will be compensated by the pinions.

R–Equalizing gear.

S–Change gear motion.

T–Double a revolution on the same shaft (Entwisle's patent); the pulley at *A* is driver on a shaft *D*; bevel gear wheel *A* is fixed; stud *E* is fast on the shaft; bevel gear wheel *B* revolves freely on stud *E*; bevel gear wheel *C* and its pulley *C'* run loose on the shaft; the rotation of stud *E* with its bevel gear wheel around the fixed bevel wheel *A* doubles the speed of the bevel wheel *C* and pulley *C'*.

U–Change gear motion; shafts *A* and *B* are disconnected and carry a loose hub and spur wheel in which is pivoted bevel pinion *T*; bevel wheel *C* is fast on shaft *A*, and bevel wheel *D* is fast on shaft *B*; any motion given to the central spur gear by the pinion shaft *E* varies the speed of the driven shaft *B* as compared to that of the driving shaft *A*.

V–Irregular circular motion.

W–Change gear motion with spur gears.

X–Ball gearing.

Figure 3.3
Herkimer's *Engineer's Illustrated Thesaurus*, pp. 172–173. Basic mechanical movements: Section 25e: Toothed gearing.

unless absolutely necessary. Engineers may use these to contact manufacturers for types of parts, subcontracting the part, or get further information necessary to design the specialized variant for themselves, and in this can presuppose those aspects of the specifications that are standardized. Thus, all of the threads for the screw devices represented in Herkimer (figure 3.2) are made according to common specifications (though different for different countries and applications). Thus, a threaded fastener will have a thread cross-section which is an equilateral (60° vertical angle) triangle while a power screw will have an "Acme" thread, with a steeper 29° angle, for lower friction in power transmission. The more complex systems in Herkimer often illustrate the variety of functions that can be achieved with a given class of mechanisms, as in the page of different ways of using toothed gearing (figure 3.3). (So if one has power delivery via a rotating shaft, this is a good page to look at, though it would not be if the power delivery were by a fluid—e.g., water or steam—under pressure.)

Herkimer is one level up from actually assembling machines out of components, such as one might do from the parts of an Erector or electronics component set. Rather it shows the kinds of functions possible with components of a given type that then can be used to assemble the design for a complex mechanism out of kinds of functionally characterized parts. However, this is still just a design sketch: it still must be checked for compatibility and availability (and cost) of the components of the relevant types. But it renders the *design problem* as a combinatorial one, one that can be accomplished in a systematic way.

The next stage is using hierarchical assembly to make more complex systems:

6. chunking, and hierarchical modularity (not just screws, but coils, starter motors, transmissions, engines, kit houses, franchises).

6.1. leads to modular assembly stages, with subassemblies constructed in different places than final assembly.

6.2. leads to specialized distribution (auto-parts stores, etc.), need for directories, and coordination with assembly stages (including "just in time" stocking, facilitated by computerized inventory control and containerized shipping).

6.3. subassemblies may be "black boxed" (which we return to below).

7. Because modular assembly is likely to be cost-effective, and also easier for parts repair and acquisition, nonmodular things may at this time be standardized or redesigned for modular construction (you can't order a standard replacement window for a Frank Lloyd Wright house, so why not design one with standard-sized windows and order them from your window catalog), often using nonoptimal but readily available components. (Many computer chips used in cars are far more powerful than necessary to accomplish their functions but are readily accessible, and adaptable, and far cheaper than custom designing a chip for the particular function at hand. Indeed, their functions can be modified or updated simply by changing their programs, which means changing the eProm installed

with them and not the chips themselves. In this way, the Intel 8088 was still alive and well long after it was obsolete as a primary processor for a PC.)

8. Standardized parts allow for premanufactured local availability, standardized assembly directions, standardized tools, and standardized training for construction and repair. These begin to suggest a radiation of consequences explaining how deeply and widely normative design standards can enter our lives.

9. With hierarchical design and manufacturing, "black boxing" will tend to occur with increasing frequency. Black boxing involves foregoing the ability to disassemble.

This may occur in several ways:

9.1. in distribution of parts (e.g., "accessory packages" for automobiles),

9.2. in manufacturing, generating subsystems that are designed to be replaced whole, or

9.3. in forgoing expertise for dealing with the disassembled black box.

9.4. but along with this, reduced need for that knowledge in the (standard) use of that part. (Of course, non-standard use may render the assumption that the more detailed knowledge is not required incorrect, and can be the source of errors or malfunctions)

9.5. Along with this we have lost skills—for example, blacksmithing, component repair. (You can no longer get a radio fixed or a car generator rebuilt, in the United States, even though the broken generator may be recycled, repaired, and resold by a firm specializing in this.) Owner manuals of cars now contain much less (if any) information on repair, which can no longer be done in your garage because expensive and specialized computer testing machines are required. The owner's manual for the Model T Ford, the first mass-produced automobile, contained information on how to perform all but the most dire forms of repair. The cars were far less reliable (and the roads more punishing!) than they are now, and one needed to know how to do a much larger variety of things on an emergency basis. (Even starting a Model T under unproblematic circumstances involved 13 steps.) On the other hand, to know how to be able to do all possible repairs at any level for a modern car would require a stultifying amount of information. "Black boxing" frees us to control our machines with far more limited information and use our minds for other things. That information, and the need to have it, has now been distributed among a wide array of professions.

10. At this stage it becomes possible to exploit the combinatorial possibilities of modular design. The catalogs for Sears kit houses (Sears 1926) allowed an enormous array of choices for alternatives of decoration, heating mode, lighting (gas or electric), and trim or quality level. Many of these choices, once made, generated a coordinated set of consequent choices that one need not attend to in detail (much like control gene cascades) and made molar adaptive decision making possible.[11] This capability was not initially a feature of

mass-production systems. Ford's competitors like General Motors started allowing choices in paint and accessories for their automobiles. This blossoming of factory installed alternatives was initially beyond Ford's capabilities. They needed to change their manufacturing system to allow this flexibility (Hounshell 1984, 13).

11. One of the intriguing patterns in our culture that emerged only relatively late (in the early 1900s) was the appearance of mechanical construction kits. These children's toys allowed them to undertake planned or invented complex construction projects with standardized parts. Tinkertoy, Erector, Lincoln Logs, Lego, Meccano, fischertechnik all provided variants, many of the parts of which could have come out of Herkimer's book. These must have made many future engineers and scientists, and fed back, creating in them a mechanical way of thinking. In the same way the explosion of the personal computer taught many young people how to program and made the computational view of the world seem natural. For kids only? In his book *The Box*, about the development of containerized transport, Marc Levinson describes how Matson shipping engineer Les Harlander designed, prototyped, and tested the arrangement for a problematic lifting spreader on the shipside crane on his son's Erector Set over Christmas vacation in 1957. On a different scale, Warwick (2003) documents how innovations in mathematical physics at Cambridge became self-bootstrapping when Cambridge graduates went back to teach in secondary schools, upping (and standardizing) the level of preparations that could be supposed for Cambridge students, who would use the acquired skills combinatorially in solving more complex problems.

This kind of feedback is crucial to the cumulative elaboration and deepening of culture and technology.

With these standardized parts and the practices involved in using them, not only in production but also in designing mechanisms as combinations of them, the ways of thought employed in solving problems became much more widespread and developed in our culture. We had a resultant adaptive radiation of types of technologies, and of variant exemplars of each type, employed for a growing array of functions, undoubtedly a factor in the enormous growth of number of products in the twentieth century noted by Murmann (this volume). This is the character and the promise of systems involving combinatorial entrenchment.

Conclusion

I discussed the five basic kinds of components crucial to an account of cultural change, their interrelations, and why extant theories of cultural evolution fell short of an adequate account. Crucial to the interaction of these kinds of entities is the cultural elaboration of scaffolding of individuals, and of the institutions and organizations that configured the culturally induced cultural breeding populations that mediate the maintenance, exchange, and elaboration of culture, and the development and skill acquisition of individuals.

The analysis of cultural evolution demands a more elaborate account of kinds of generative entrenchment, and how it is mediated in complex evolving systems, one presented and distinguished here for the first time. One type, combinatorial entrenchment, involving the emergence of a combinatorial alphabet of alternatives allowing an explosive and systematic growth of generated variations is discussed at more length. Emergence of such a system is perhaps the most important kind of evolutionary event facilitating innovation, and an explosive growth of complex entrenched structure results, generating a set of elements that become sufficiently standardized that they become in effect foundational.

I discussed cases from biology and from cultural evolution. I then elaborate the labored emergence, in nineteenth-century arms production, of interchangeable and standardized parts. The more molar and systematic character of such a system and the coordination of its parts is seen in this extended example to require diverse modes of scaffolding in its support. As "armory practice" spread through other industries, it engendered other changes, and the net effects were major elements amplifying the industrial revolution. This involved correlative changes in the kinds of cultural items acquired and exchanged, and in the scaffolding training and skill acquisition of individuals, in the practices of manufacturing and labor, in the creation of a number of new organizations, institutions, and infrastructure involving virtually all of the scaffolding provided by the kinds of artifacts we are familiar with today. All of these serve to illustrate that changes in one of these kinds of elements of culture may have far-reaching implications for changes in the others. And scaffolding and entrenchment are at the center of these changes and show themselves to be central elements of culture. Indeed, the amplification of and growing multiplicity of kinds of scaffolding may be regarded as one of the distinguishing characteristics of culture. Analyzing entrenchments should be a crucial tool in its analysis.

Acknowledgments

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Notes

1. Gerson (this volume) follows Hughes in defining culture as a system of institutions made up of conventions. An institution is a collective capacity to carry out some task, "a collective enterprise carried on in a somewhat established and expected way."

2. This locution is misleading—the ideas of "feedback" and of a life-cycle are misnomers: they are helices in space-time with the *recurrence in sequence of similar events.*

3. This process is misleadingly called "program maintenance" and often requires major rewriting of the program to maintain something approximating the "look and feel" of its ancestor while operating with very different hardware and software. It is really "program evolution." Biological evolution has something similar, with substantial genetic change occurring while maintaining similar appearance and operations at a higher functional level in the organism. See Andreas Wagner (2006) on robustness.

4. Programs allowed (usually limited) "backwards compatibility" with the preceding version or two of the software, but I have had to migrate an old Mac OS "MacWrite" file through two computers with older operating systems running older versions of "WORD" to bring it up to date so that it could be read and recovered.

5. Philosopher Robert Brandon relates how as an IBM summer intern during college, he was expected to wear a three-piece suit to work, even though he was never in a place where he might see a banker! (personal conversation)

6. Business firms have an indeterminate life span, with intense selection, especially when smaller (Murmann, this volume), and reproduction may occur, as when a group of individuals in a firm leave to start a new company, showing heritability of much of the knowledge base and culture of the parent company, but hybridizing with others hired from other lineages. However, there is no necessary senescence or reproduction, and indefinite change is possible, including acquisition of other firms either to get larger in the given market or to diversify.

7. The story is more complex: each of us is an ecosystem for 5,000–10,000 endoparasitic and endosymbiotic species that we exchange with each other, increasing similarities with the horizontal transmission of cultural systems.

8. Written language also originated independently at least in China and in the New World.

9. Stoff notes that the automotive industry which took on much of the work at the start of World War II was not initially prepared for aircraft production and ended up producing tanks, trucks, jeeps, and other military surface vehicles: high-performance aircraft required significantly closer tolerances, and higher reliability, and a bomber involved roughly 40 times as many parts as an automobile. This involved the creation of new aircraft factories and rapid expansion of the aircraft industry (Yenne 2006), with much more subcomponent manufacture and assembly, usually by subcontractors. On the growth of standards, the American Society of Mechanical Engineers now lists over 600 publications on standards in diverse areas governing manufacturing and testing, and used in over 100 countries, giving worldwide mechanical compatibility in crucial respects (http://www.asme.org/kb/standards). And other bodies set standards for technological production. Thus IEEE is a major standards setter for electrical, electronic, and information processing technologies. These are backed up by conformity assessment programs that assess and certify whether manufacturers are meeting the standards.

10. The "motifs" unearthed by Alon (Milo et al. 2002; Alon 2007) of simple network elements found widely in genetic, neurological, ecological, and electronic circuit networks suggest that similar features apply both in organic and engineering realms. Parallels with this case are worth further study.

11. The case of the Sears kit houses has many interesting components, and involved innovations in kit manufacturing, house design, marketing, and financing. This story is told in detail in Wimsatt and Griesemer (2007).

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