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# A Functional Perspective on the Emergence of Dominant Designs

*Models of long-term product innovation depict the trajectory of products through an evolutionary selection metaphor in which product designs converge toward a dominant design. The product innovation literature favors trajectory descriptions based on the physical architecture of products while neglecting to account for the functional architecture. This paper offers a new way to explain the life cycle of product innovation by identifying motifs that describe a product's functions. Functional motifs are recurrent function blocks across multiple generations of designs for a product. A collection of functional motifs defines the functional architecture of the product. Using some key examples from innovations in sewing machines, the paper illustrates the occurrence of motifs as the basis for detecting the emergence of a dominant design. Patents related to the sewing machine over 177 years are analyzed to identify functional motifs characterizing the evolution and convergence toward a dominant design. Results show that motifs do not change over long periods once a dominant design emerges, even though components continue to change. This observation confirms a view of dominant designs as a technological frame but refutes the notion that design no longer matters in the era of incremental change. These motifs refine our understanding of how designs evolve along a particular path over the course of product innovation.*

*Keywords: Functional Reasoning, Machine Theory, Product Design*

## 1 Introduction

Numerous studies assume, investigate, or develop the idea that products improve over time by following prescribed patterns. Evolutionary models depict products as evolving through a process of variation, selection, and retention [1]. Viewed in this evolutionary perspective, product improvements over time are seen as defying systematic modeling because they follow idiosyncratic or random processes with a path-dependent trajectory determined by the resources created by a specific technological development [2]. One way path dependency manifests is in the technologies embodied in key components of a product. Technologies improve at different rates [3,4]; the choice to specify one technology over another through the key components, therefore, determines a product's overall improvement potential [5]. Another way path dependence manifests is in the physical architecture of the product. This physical architecture perspective has become the accepted way to understand the trajectory of product improvements over time. The unit of analysis of an architecture is either the entire product or a subsystem [6]. Researchers study the evolution of a product based on observations of its physical architecture. For example, the evolution of commercial jetliners can be described by the change in the location and number of engines. The hypothesis is that product architecture shapes the dynamics of technology improvement; the rate of technology improvement is not independent of product architecture. Fujimoto [7] showed that the rate of innovation of passenger cars depended upon the modularity (simple, standardized interfaces between components) or integralness (complex and customized interfaces between components) of the vehicle architecture. A product architecture can cause technology choices to endure and become increasingly entrenched due to the cost of change depending upon the extent to which a product architecture tends toward higher levels of complexity. The configuration of the product's structural elements can become increasingly interconnected such that a change to one element entails changes to other elements [8] toward an infinite regress [9]. Once a company commits a specific product architecture, only at high cost and with rarity does a company change that architecture [10].

Eventually, the industry converges toward a single dominant design for a product. For example, the current dominant design for commercial jetliners is one engine mounted underneath the wings. The dominant design represents the market's acceptance of a particular product's architecture [6]. Simply put, if the product architecture no longer changes, then a dominant design has occurred.

Our prior research suggested that focusing on the physical architecture can obscure how the functional architecture affects path dependency in product improvement over time. In other words, the choice of a particular combination of functions—as opposed to components—and the architecture of those functions will set a path dependency that *precedes* the component design and physical architecture. Our hypothesis is that a functional architecture, which is expressed in a physical architecture, influences product evolution. The complexity of a functional architecture [11] creates technological lock-in due to the cost of changing a functional architecture *even if* the physical product architecture remains modular and amenable to change. Over time, the interplay between a product's functional and physical architectures may produce specific characteristic patterns of product evolution that are unnoticeable in a study of the physical architecture alone. Identifying the improvement-enabling or improvement-curtailing properties in functional architectures can refine our understanding of why products evolve along a particular path throughout the life cycle.

In this paper, we extend this line of thinking to address the emergence of a dominant design from a functional perspective. The paper focuses on identifying motifs associated with the functional architecture of a product to demonstrate that the emergence of motifs heralds the emergence of a dominant design. We define functional motifs as groups of functions within a complete functional architecture that recur significantly across the functional

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architectures of multiple generations of a product.

We study the product innovation trajectory of the sewing machine from the periods 1845–1880 and 1900–2022. Section 2 provides the theoretical background underpinning the choice of functional architecture as a means to describe the evolution of the sewing machine and detect the emergence of a dominant design. Section 3 describes the patent selection process used to obtain technical data on sewing machines and the approach taken to identify functional motifs in the functional architectures of sewing machines across multiple generations. In Section 4, we describe the motifs identified in the sewing machine's functional architectures and discuss their use in understanding design trajectories. Section 5 offers concluding remarks on how this work updates theories about product evolution and the importance of focusing on functional architectures in predicting product evolution.

## 2 Background

The classic model of product innovation by Abernathy and Utterback [12] hypothesizes that a new product is introduced into the market when a scientific breakthrough or significant performance improvement occurs. Multiple competing designs for this new product will emerge as firms test different combinations of functional and structural elements to match product performance and cost with customer preferences. That is, firms (initially) compete on product differentiation. Eventually, the industry settles on a dominant design encompassing an industry's selection of constituent technologies embodied by the physical architecture. Social, political, and organizational dynamics drive firms' decisions to select and converge on a dominant design [1]. Once a dominant design emerges, the basis of competition shifts. Companies should compete on production process efficiency rather than performance or even the "design" of the product *per se*.

Many scholars have argued that this reliance on the physical architecture of a product to exemplify a dominant design needs to consider the coalescing of technological principles that precede the selection of components and their configuration into a product. The idea that dominant designs represent a convergence of a technical understanding across an industry and not simply an assemblage of particular structural elements was theorized by Kaplan and Tripsas [13]. Kaplan and Tripsas [13] introduced the concept of technological frames to explain a technology trajectory. Technological frames encompass the (technical and market-oriented) knowledge underpinning products and the embodiment of that knowledge in the physical realization of the product. This theorizing departed from the prevailing view in industrial and organizational economics that economic or organizational factors such as demand and technical competence drive the emergence of dominant designs.

Our research builds on the concept of using technological frames to analyze the trajectory of the design of a product. Technological frames in the context of sewing machines encompass the multiple elements of a successful machine (rather than a human), described below, to combine pieces of fabric using a thread. In this paper, we represent a technological frame with the concept of functional models. Goel [14] equates functions with technological frames, stating that functions are "mental abstractions that enable hierarchical decomposition of a complex system into subsystems" [14, p. 204]. Functions are central to defining a technical system because they characterize the reasoning associated with a technical system, from its goal to its structure [15]. Functional models represent designers' knowledge about the technical systems they design [16]. They can take several forms [17], including hierarchical descriptions of the flow of material, energy, or information through the system [18] and how those flows are transformed. They can also include the human and technical processes that work together to achieve a specific outcome. In this research, functions refer to an abstraction of applied physics principles that a designer has intentionally selected and assembled to act on a set of inputs to produce a desired output. A functional architecture captures the knowledge a designer must have and "put together" to build a technical system that works on the physical world in a desired way.

We explore the idea that changes in a functional architecture can depict the trajectory of a product's design over time by analyzing the functional architecture of the sewing machine. Centuries of tinkering and experimentation with the manual process of combining thread and cloth with a needle preceded the sewing machine's historical development. By 1790, Thomas Saint of Britain was issued patent 1,764 for a device regarded as the world's first sewing machine design. However, this characterization did not happen until the late 19$^{th}$ century, and thus Saint's invention likely did not play a significant role in the further development of sewing machines. Nevertheless, manufacturing improvements such as low-cost cast iron, novel fabric weaving techniques, and increasing demand for manufactured textile goods spurred many inventions about the sewing machine. American and British inventors continued to produce clever and interesting designs throughout the 1800s as the basic functional architecture emerged [19]. According to the classic technology life-cycle model, this period of the early 1800s represented the era of ferment. By 1851, the basic functional architecture was established, and the first commercially successful sewing machines had been patented. The definitive history book *The Sewing Machine: Its Invention and Development* [19, p. 19] summarizes six elements of the functional architecture associated with the first commercially successful sewing machines (with emphasis added to highlight the essential functions):

> The requirements for producing a successful, practical sewing machine were: a **support for the cloth**, a needle to **carry the thread through the fabric** and a combining device to **form the stitch**, a feeding mechanism to **permit one stitch to follow another**, tension controls to **provide an even delivery of thread**, and the related mechanism to **insure the precise performance** of each operation in its proper sequence.

These six 'functions'—carry thread, form stitch, permit one stitch after another, provide thread delivery, and ensure precision—form the basis of sewing machine innovation throughout the last 180 years. As the passage implies, it was an assemblage of specific *functions* that defined a working sewing machine, not the physical architecture itself. Until the industry had this technological frame for a sewing machine, a successful machine was not possible. Inventors toyed with this functional architecture to produce thousands of designs, some of which align closely with a dominant functional architecture and others that diverged with more radical functional architectures. As such, the history of the sewing machine provides an interesting case to test the idea that functional architectures can better depict the trajectory of change when changes (or lack of changes) to the physical architecture create ambiguity in knowing when a product is evolving from one era to another.

## 3 Methods

The emergence of a dominant design can take place over many years and decades. Therefore, a historical case study is appropriate for observing product innovation and stabilization to observe how the concrete details of the case (the functional motifs of a sewing machine) contribute to the larger system (long-term product innovation). The purpose of the case study is not to develop generally applicable rules but, instead, to understand details of the larger system that support conclusions otherwise obscured in a study of many product categories [20].

We derived technical design data for sewing machine design innovations from patents for sewing machines. The US Patent and Trademark Office (USPTO) has granted thousands of patents to innovations associated with the sewing machine over the past 200 years since the first machines were invented. While it could be possible to create a functional model for each patented innovation, our intent for this analysis is to sample the sewing machines that have been designed and commercialized to determine whether changes are occurring or have largely ceased at the functional level.

We identified functional changes in sewing machines in three phases, conducted in iterations as patterns emerged in the data to guide more effective patent searches. The first phase aimed to identify sewing machine patents relevant to the research goals. The book *The Sewing Machine: Its Invention and Development* [19] provided a list of crucial early sewing machine patents. Then, using code written in *R*, we generated a list of terms relating to frequently patented sewing machine innovations (generally associated with the six 'functions' of a successful machine described above). We used these terms to search the US patent database, resulting in a compilation of patents for each innovation from 1900 to the present day. In the second phase, we created function decomposition models (functional models) of each patent using existing functional decomposition methods adapted to sewing machines. During the third phase, we measured the functional differences between various generations of sewing machines and their corresponding functional models using graph edit distance to identify functional motifs. Additionally, we compared the functional variances with visible changes in the physical architecture.

**3.1 Phase 1: Patent Selection.** We aimed to identify patents that show successive improvements in physical and functional architecture. The patents are divided into two groups. The first group consists of early and important sewing machine patents from the middle of the 19$^{th}$ century (towards the end of the industrial revolution). This group enabled observation of the era of ferment—the period when sewing machine manufacturers were proposing various functional approaches to a successful sewing machine, and the industry had not yet settled on a dominant design. The second group consists of sewing machine patents from 1900 to the present and is intended to represent the era of incremental change.

For the period up to the 19$^{th}$ century, we turned to the book *The Sewing Machine: Its Invention and Development* [19] by Grace Rogers Coopers. This book is widely considered the definitive text on the history of the sewing machine. The book identifies twelve patents that defined early US sewing machine designs, including four patents preceding the first commercially successful machine and eight patents developing essential elements of a sewing machine. Table 1 summarizes these patents. We chose additional patents from a set of manufacturers described in this book who have substantially more patents (7 or more, based upon a frequency analysis of the number of patents assigned to various inventors) than other inventors. There are six such inventors: W. B. Bartram (7 patents), David W. Clark (8 patents), James E. A. Gibbs (7 patents), James S. McCurdy (8 patents), Isaac M. Singer (9 patents), and Charles H. Wilcox (7 patents) [19].

**Table 1 Significant early US sewing machine patents**

| Patent Number | Author | Year |
|---|---|---|
| 2,466 | Greenough | 1842 |
| 2,982 | Bean | 1843 |
| 3,389 | Corliss | 1843 |
| 3,672 | Rogers | 1844 |
| 4,750 | Howe | 1846 |
| 6,099 | Morey/Johnson | 1849 |
| 6,439 | Bachelder | 1849 |
| 6,766 | Blodgett/Lerow | 1849 |
| 7,776 | Wilson | 1850 |
| 8,294 | Singer | 1851 |
| 8,296 | Wilson | 1851 |
| 9,041 | Wilson | 1852 |
| 12,116 | Wilson | 1854 |

Unlike the first group, patent selection for modern (1900 onward) patents does not rely on historical records and can be partially automated due to the availability of digitized patent data. Patents in this period rarely describe full machines and can be grouped into categories representing subsystems based on key search terms. As this group is exceedingly large, we employed computational tools and a systematic database search to identify key terms and select patents. First, we downloaded all US patents having the exact phrase "sewing machine" in the title from the Google Patents database. Then, we analyzed patent titles using a natural language algorithm and clustering analysis in *R* to identify interesting and frequent key terms, or phrases, in the titles. These phrases relate to components implementing critical functions in a sewing machine, such as the presser foot or the needle bar, and thus represent collections of important sewing machine innovations. The code produced a list of 12 phrases relating to sewing machines and associated with high patent activity. A given phrase, along with the phrase "sewing machine", was used to search the Google Patents database again along with the following criteria:

(1) Patent Office: US
(2) Language: English
(3) Status: Granted
(4) Type: Patent
(5) Publication date: 1900 to present day
(6) Excluded terms: hat, shoe, book, button, safety, industrial

This was repeated for each phrase generating 12 separate lists of patents from 1900 to the present. From each list, we selected at least one patent within each quarter century between 1900 and 2025, as well as highly cited patents. Through this process, we identified 106 patents.

In total, 164 patents were identified during patent selection. All of the patent abstracts were read to determine the extent of the innovations (patent claims). We were interested in identifying patents that made claims to new functions (Later, in the section on graph edit distance, new functions are tantamount to a new function block.) or new ways of achieving existing functions (considered in the graph edit distance as a substitution of one or more function blocks) rather than enhancements to existing functions. Ninety-seven (97) patents were excluded from further analysis, resulting in 67 patents analyzed in the next phases (33 machines from the era of ferment and 34 newer machines from the era of incremental change). The exclusions occurred for two reasons:

(1) The patent showed no functional difference from other patents. In other words, it was likely that we had reached saturation in the sampling of patents to observe functional change. Additional patents would not yield new information. Instead, the patent claimed performance improvement through design modifications to one or more components. The functional model for the machine described in the patent could be assumed to match that of an already existing model. Subsystem patents in particular often showed complex assemblies, but a review of the patent abstract and core functions revealed that the patent yielded no new functionality.
(2) More patents in the modern era were identified as interesting than could feasibly be modeled due to the complexity of the functions described in the patent. Future work will reexamine these patents to determine whether they need to be modeled.

The researchers are also in possession of a Husqvarna Viking 950, a complete sewing machine released in the 1980s. Analysis of this machine will assess the functional difference between early patent designs and a complete sewing machine that demonstrates an integration of relatively modern solution principles.

**3.2 Phase 2: Functional Decomposition.** In the second phase, we represented the mechanical design of sewing machines and their subsystems, as described in patents, as functional models through a process of functional decomposition, or functional modeling. Functional modeling is a well-established method for

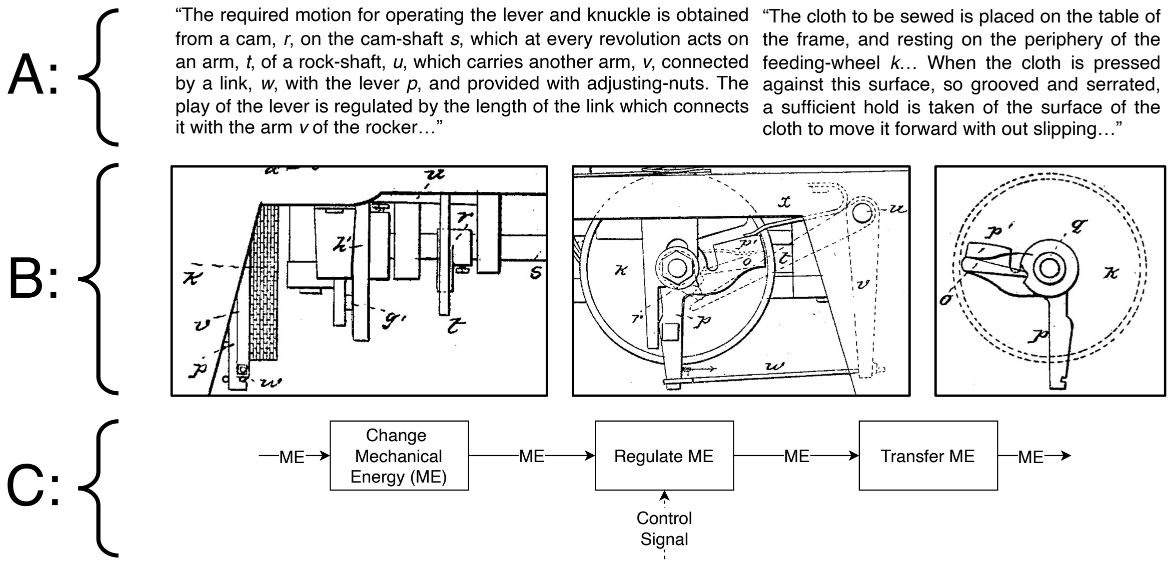


**Fig. 1 Methodological demonstration of the functional analysis of sewing machine patent 8,294**

abstracting a physical product or system to its electro-mechanical functional architecture. The goal is to describe the design intent in functional terms. Functional modeling aims to formalize the language (usually through an ontology) and the process by which the structure of a product's mechanical functions is defined. Functional models typically consist of a flowchart, or graph, with nodes representing functions and edges representing flows between functions.

The production of functional models is largely a manual process. Some common challenges and critiques of functional modeling focus on the subjective nature of this method [15,16]. We investigated automated techniques [21] but decided that none were able to integrate the analysis of pictorial and linguistic descriptions of mechanical devices at an adequate level of detail to determine their primary function. We derived functions in sewing machines by understanding the ensemble of descriptions of the purpose of components, design principles, and inventor intent—the totality of which is, at present, only understandable through human expertise and intuition. In the rest of this section, we outline steps taken to address this uncertainty through training and duplication.

The ontology for functional modeling in this research is based on the functional basis [18,22]. The functional basis explicitly defines a set of functions (verbs) and flows (nouns) that encompass possible functionality in mechanical systems. Stone calls for modeling the most "elemental" functions in a design [18]. Common functions in a sewing machine are "secure", "regulate", and "change", and flows may be energy (usually human, mechanical, or electrical energy), material (i.e., the fabric and the thread), or signal. In this paper, we name the instance of a function and its inflows and outflows as a *function block*. Each function block consists of a function-flow ensemble. The broad guidance for functional modeling results in variable approaches to functional modeling styles, which illustrates the under-defined nature of functional modeling [17].

Use of the functional basis ensured a high level of accuracy in the functional models. The functional basis was developed to be widely applicable to any electro-mechanical system and the descriptions of functions and flows are detailed and orthogonal. However, the process is not exact and can be subject to error based on the background of the person conducting the analysis. Therefore, the goal in functional modelling is to follow practices that achieve repeatability [23]. To achieve these outcomes, we adhered closely to the definitions of functions and flows in the functional basis while increasing the level of consistency in the identification of functions and flows in the sewing machine patents. We achieved these outcomes in several ways.

First, we framed the functional analysis through a lens of "design intent". The format of patents aided in the understanding of design intent. All patents are presented as a detailed written description augmented by figures at varying levels of detail. While the form may be understood from an examination of the figures, the design intent is best learned from the written description, provided the inventor was sufficiently clear about their intentions. The functional model therefore most closely follows the written description. Conversely, if the written description excludes a certain design decision or component, it was important to avoid filling in that "gap" in the functional model.

Second, We relied on several additional clarifications of the functional basis to improve the reliability and repeatability of the functional modeling.

(1) The state of the art provides that functional decomposition is most accurate and useful when functions and flows are limited to the "second level" of the functional basis [24].
(2) We approached "form-agnostic" functional models by eliminating any indication of form within each function. *Groups* of functions must not indicate design form. This comes from "over-modeling" the design by assigning a function to individual components rather than considering the broader design intent of an assembly of components.
(3) We developed and applied an ontology of common components and their functions to improve the repeatability of functional modeling across machines. This approach follows established guidance to codify relationships between the components, functions, and flows of products as a step toward automating functional modeling [25]. Since functional modeling is based upon natural language instead of algorithmic definitions, and the relationship between components and their function(s) are usually specified in the patent text, certain components could be named by the functions they accomplish. These components recur across many machines. Table 2 lists common component assemblies and the functions they implement.

Figure 1 illustrates an example of the functional analysis for a sewing machine patent. This example pertains to a group of functions related to the flow of mechanical energy (ME) to the cloth feed wheel in patent 8,294, a motif documented in many patents. The functions are Change ME → Regulate ME → Transfer ME. The process for modeling this patent is as follows. First, read the

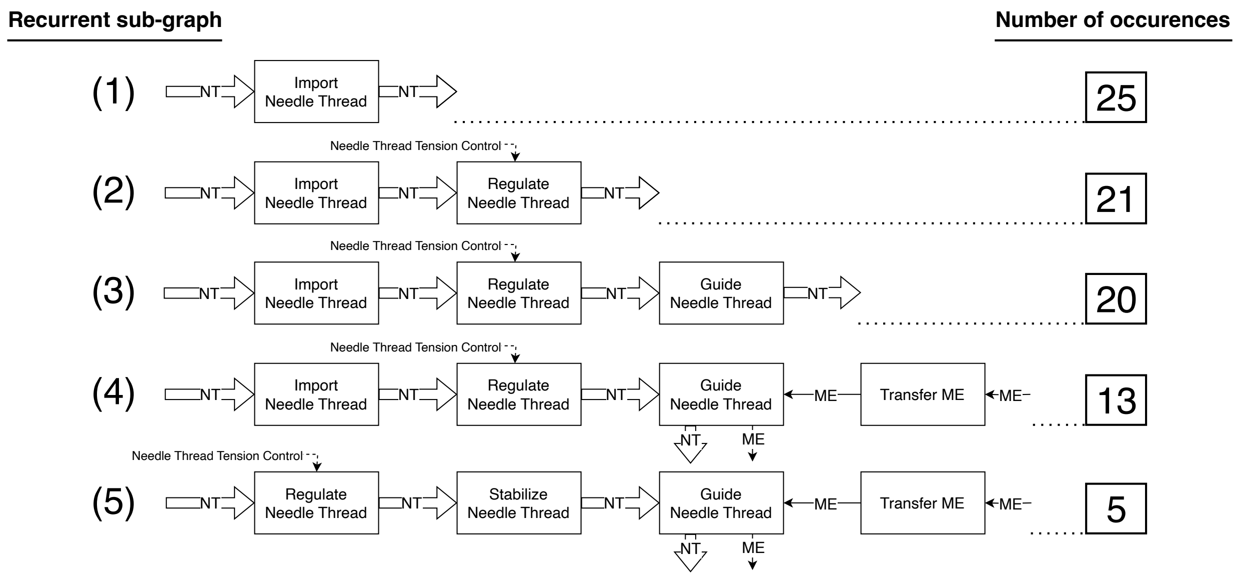


**Fig. 2 Methodological demonstration of functional motif identification: number of occurrences for five successive recurrent sub-graphs**

**Table 2 Examples of common sewing machine component-function correlations**

| Mechanism | Function Block |
|---|---|
| Cam mechanism | Change ME |
| Scotch yoke | Change ME |
| Reducing gear mechanism | Change ME |
| Needle (any type) | Transfer ME (to Thread 1) |
| Rotary hook | Transfer ME (to Thread 2) |
| Vibrating Shuttle | Transfer ME (to Thread 2) |
| Feed-wheel | Transfer ME (to Cloth) |
| Static presser-foot | Secure Cloth |
| Reciprocating presser-foot | Stabilize Cloth |
| Thread length control device | Regulate ME |
| Thread tensioner | Regulate Thread (1 or 2) |
| Driveshaft to multiple outputs | Distribute ME |

entire written text to learn about the context and purpose of the design (**A**). Then, follow along the progression of component descriptions in the text while also reading the figures to build a mental model of the structure of the design (**B**). Readers are encouraged to take notes at this stage. Next, return to the text to clarify assumptions about the functionality that might be implied by the figure. This step ensures that the functional model only contains the information described in the text, thus capturing design intent. Finally, construct the functional model (**C**) based on the second level of the functional basis and keeping in mind the clarifications listed above. This is an iterative process that requires several back-and-forth passes through the patent to continue to clarify assumptions about the functionality. Often a component or subsystem has multiple functions, and the reader should identify and include only the primary functions, rather than all possible functions.

Fourteen (14) undergraduate research assistants (URAs) were trained on the functional decomposition and modeling process for sewing machine patents. All of the URAs had taken the junior-level mechanical design course, which teaches functional modeling, and the mechanical component design course. They had received a grade of B or higher in both of these courses. The URAs were trained on the architecture (including subsystems and their components), operation (how to sew), and functionality (functional elements of a successful sewing machine) of sewing machines. For example, they were shown the presser foot and explained its function according to the functional basis. How this information is presented in the language of patents was also shown. Each patent was read in full by each URA. Two URAs each independently created a functional model of the patent. Then the URAs compared models and discussed and resolved discrepancies. Unresolvable discrepancies were discussed with a member of the research team (an author) to reach a consensus. Finally, a member of the research team reviewed each model for accuracy.

**3.3 Phase 3: Functional Motif Identification and Analysis.** Our goal was to identify motifs in the data by comparing each patent's functional and physical architectures. Robust analysis tools for functional models are unavailable or only apply to a particular device. Therefore, we took a general search approach to identify motifs in the data. Specific methods used include visual comparisons of functional models assisted by measures of graph edit distance (GED) to identify the degree of change between pairs of functional models. The rest of this section describes the process for the identification and analysis of motifs in more detail. Figure 2 illustrates an example of the identification process.

To find the motifs, we followed an established procedure [26] to identify recurrent sub-graphs and the criteria for ascribing a recurrent pattern as a motif. A motif-finding algorithm searches the adjacency matrix of a network for all nodes connected to an initial node up to an n-node sub-graph. We adapted this technique to identify motifs qualitatively. The process begins by identifying a function block and its inflows and outflows. This function block is usually associated with a subsystem that implements one of the critical functions of a successful sewing machine. Then, we successively increase the sub-graph into a 2-node sub-graph, 3-node sub-graph, etc., until we find the largest sub-graph that contains matching function blocks repeated across multiple patents. The largest set (n-node sub-graph) of recurrent function blocks is a motif. Finally, we concatenated motifs for each element of a successful sewing machine to produce a *dominant functional architecture*, a functional architecture comprised of the functional motifs.

The motifs in dominant functional architecture were first created based on the 33 functional models of early US sewing machine patents from the era of ferment (pre-1900), as these models represented sewing machines that demonstrated the complete functionality required to form a stitch. However, we validated that the motifs persisted through the era of incremental change (1900–today).

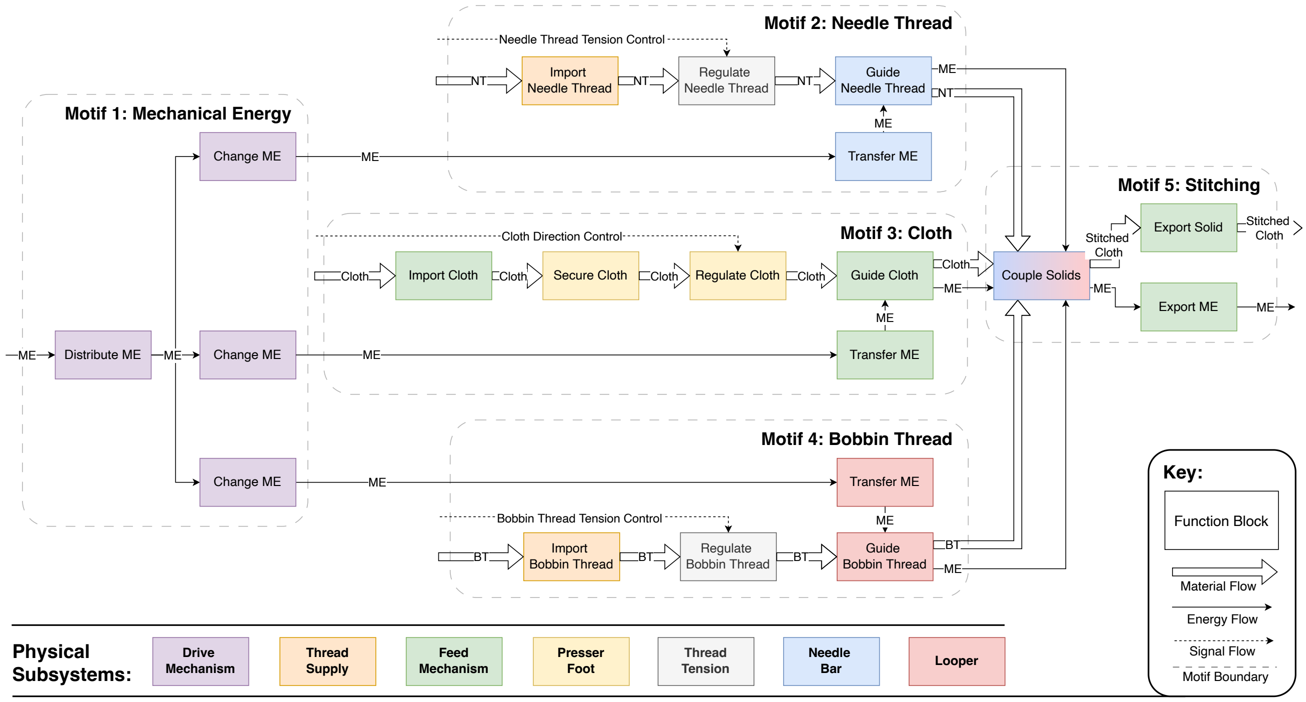


**Fig. 3 Sewing machine dominant functional architecture with dashed lines around the five functional motifs and color coding to indicate the relationship between functions and physical subsystems**

In Fig. 2 we began with a single function block, "Import Needle Thread", in sub-graph (1), selected due to its frequent occurrence across functional models. We increased the size of the sub-graph by adding function blocks that resulted in the highest rate of sub-graph occurrence as in sub-graphs (2), (3), and (4). Sub-graph (4) occurred sufficiently frequently, 13 times, to be labeled as a motif. Occasionally we saw a sub-graph similar to (4) except with an additional "Stabilize Needle Thread" block. This sub-graph, (5) only occurred 5 times and is below the threshold to be considered a dominant motif. We confirmed the decision to exclude sub-graph (5) by verifying that a majority of the functional architectures in the era of incremental change also lacked the "Stabilize Needle Thread" function block.

We then compared functional models to the dominant architecture to determine the degree of alignment. We used visual comparisons and graph edit distance (GED) to identify isomorphic subgraphs. Graph edit distance was implemented as a metric of difference between pairs of functional models. Functional models are graphs with nodes (functions) and edges (flows). Prior research in vector and network-based measures of product similarity recommended that the GED is an appropriate metric when the products are of similar complexity and are not expected to be highly dissimilar [27]. The GED [28] is the sequence of operations that transform a source graph into a target graph. A GED algorithm calculates the minimal set of operations that can transform a graph representation from a source model to a target model. Graph edit transformations consist of three operators: node insertion or deletion, edge insertion or deletion, and node or edge substitution. Each operation (node addition, deletion, or substitution) is a single transformation. A node addition is tantamount to the addition of a function; a node deletion is tantamount to the deletion of a function. A node substitution is regarded as achieving the same design intent in a new way. The total transformation is the sum of all the operations in the sequence. Several feasible sequences are possible to transform a source graph into the target graph. GED is reported as the fewest transformations.

We used the NetworkX [29] Python module to calculate an exact GED between functional models. graph_edit_distance(G1, G2) [30] takes two graph data structures (G1 and G2, directed or undirected) as its arguments and calculates the number of edits (including label renaming, node deletion/creation, and edge deletion/creation) required to change one graph data structure to another.

## 4 Results and Discussion

This section presents the results of the methods, including examples of observed functional motifs and how the motifs relate to historical context. The methods identified a variety of motifs in early sewing machine functional models. Some motifs are found in most functional architectures, while others are only associated with historically significant or commercially successful machines. Additionally, certain motifs are associated with frequently patented subsystem innovations. The results show that a dominant functional architecture emerges early in the development of sewing machine design. The graph edit distance calculations identified the emergence of a functional architecture as a reduction in the value of the GED from one generation to the next. Continued invention competes on the correspondence between functional and structural (components) elements within the dominant functional motifs. Machines implementing the dominant functional architecture are found to show minor variations in their functional architecture, which can largely be attributed to increased control and the effect of electrification.

**4.1 The Dominant Functional Architecture.** The dominant functional architecture of sewing machines is characterized by an assembly of five functional motifs, shown in Fig. 3. Per the method described in section 3.3, the motifs are the largest repeating sub-graphs across most patents (in other words, across multiple generations for the design of a sewing machine). These motifs appear frequently either on their own or alongside other motifs in sewing machine functional architectures. In the figure, motifs are linked together in a unified architecture because input and output energy and material flows align (and the motifs are frequently grouped this way). This architecture has a distinct visual modularity, consisting of three branches for each of the needle thread, the cloth, and the bobbin thread (motifs 2, 3, and 4), sandwiched between motifs 1 and 5.

The motifs are delineated in Fig. 3 by dashed borders. Motif 1 on the left side consists of the division ("distribute") of mechanical energy into three branches, then conditioning ("change") of that energy. Mechanical energy is the only flow in and out of this motif. The 5th motif on the right side is the convergence of material and mechanical energy flows into a single "couple solids" block, representing the complex motion of bringing together the two threads and cloth into a stitch. This motif also shows the stitched cloth and mechanical energy leaving the system. The motifs for the needle and bobbin thread (2,4) are identical except for the difference in material. They consist of the import of thread and the transfer of mechanical energy to the thread to move and guide it through the system. Additionally, a control signal for thread tension goes to a "regulate" block. The motif for the cloth (3) is similar to 2 and 4 with the addition of a "secure cloth" function. The "regulate" block in this motif represents the ability to control the direction of cloth movement. The in and out flows for these three motifs are a single flow of mechanical energy and the respective material.

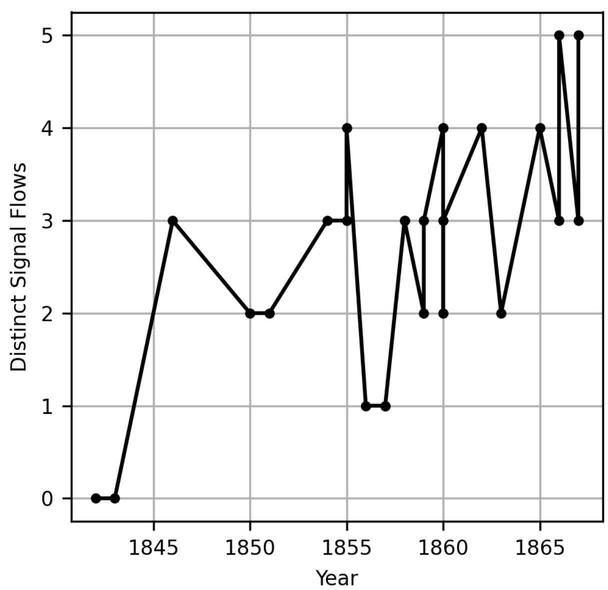


**Fig. 4 Number of signal flows in functional models of early sewing machine patents granted between 1842 and 1867**

While patents increasingly align with the dominant functional architecture into the 20th century, we noticed one constant change. Fig. 4 graphs the number of signal flows in functional models of early patents between 1842 and 1868. While there are very few control signals early in the design evolution of the sewing machine, after the emergence of a dominant functional architecture, the number of control signals increases. This finding shows that after the era of ferment, design competition shifts to the design of components that implement functions to increase precise control. If firms are saving manufacturing costs during the era of a dominant design, they are likely investing the manufacturing cost savings into the design of new control subsystems.

Color coding in Fig. 3 represents the relation between functions and physical subsystems in the dominant functional architecture of a sewing machine. The seven subsystems are derived from the list of innovations described in Section 3.1, and thus are terms corresponding to significant patent activity in the 20th and 21st centuries.

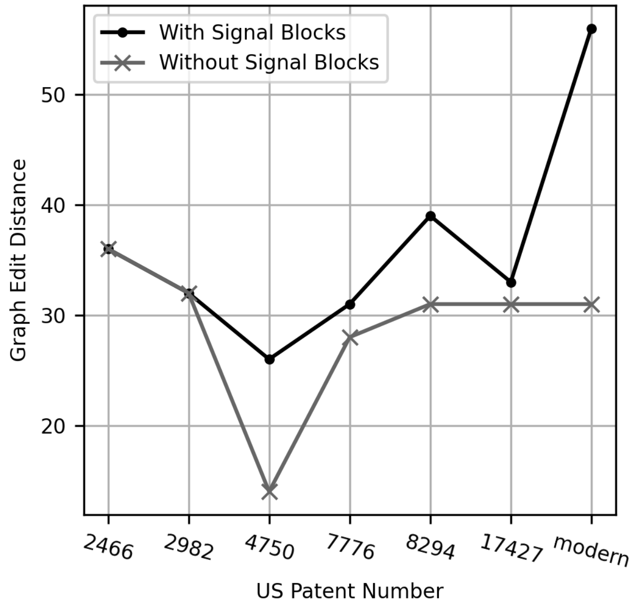


**Fig. 5 Graph edit distance between the functional models of seven sewing machines and the dominant functional architecture**

Functional models of patents from the innovations fit within the dominant functional architecture and generally align very closely with it. As with early machines, differences between patents—especially relating to performance, reliability, or usability—do not necessarily result in differences between their functional models. Significant change does occur, however, concerning control signals and regulate blocks. Just as in early machines, a significant change occurred as inventors found new ways to add finer control.

Figure 5 shows the graph edit distance between the dominant functional architecture and the functional models of seven influential sewing machines. We calculated GED two ways: first with the complete functional models (blue line) and second with all control signals and "regulate" blocks removed (orange line). Control signals are important but do not usually result from more profound functional architecture differences between two models. Removing them reduces "noise" in the comparison and demonstrates the impact control signals have on specific machines, such as the modern machine.

As expected, the graph edit distance attains the minimum value with patent 4,750 granted to Elias Howe, Jr. in 1840. This result suggests that the dominant functional architecture emerged in Howe's design. Corroborating this result, historians generally give full credit to Howe for the invention of a *practical* sewing machine [19]. While the GED increased afterward, it ceased to change after patent 8,294 (granted in 1851) all the way to modern patents. Therefore, even though Howe's machine does not look like the current dominant design for a sewing machine, such as the Husqvarna Viking 950, the dominant functional architecture emerged before the dominant design (when interpreted as a design having a common physical architecture across a product offered by multiple competing manufacturers).

While the graph edit distance helped gauge the degree of change in functional models, we determined that the GED did not have sufficient resolution to precisely track the functional changes over time. The GED has no mechanism to account for the importance of change between two graphs because, in the absence of empirical data, the GED treats the cost of all changes (node/edge deletion, addition, or substitution) equally. GED should, therefore, only be taken as a preliminary indication of the degree of change. Some functional changes may have greater significance or represent a fundamental restructuring of the interpretation of the dominant architecture. For example, substituting functions would be a more significant change from an engineering perspective. However, the substitution change would appear identical to the simple addition of a control signal when viewed from the perspective of GED.

Historically, patent 4,750 has had an outsize impact on future patents and is foundational to sewing machine design for decades after its issuance. While inventors continued experimenting with divergent functional architectures well into the 1870s, it is clear that Howe had assembled the dominant functions by 1846. Patent 4,750 was the first to demonstrate alignment with most of the dominant functional architecture, perfectly aligning with four of the motifs and near aligning with the other two. The graph edit distance between the dominant functional architecture and patent 4,750 is low at 27 transformations (if including signal blocks). Figure 6 shows the functional model of the modern sewing machine, with highlighted blocks that match up with blocks in patent 4,750. There is a significant carryover from patent 4,750, despite 131 years between their inventions. The functional architecture of the modern machine shows distinct similarity with those of early sewing machines, demonstrating the endurance of the dominant functional architecture. One reason for the differences between modern machines and early ones is electrification. Electrification enables greater control and more accurate interaction with the machine, leading to the addition of "control" signals and "regulate" blocks in the functional model.

The perceived stability of the dominant functional architecture may be a result of the patent sampling process. The sampling process identified the most common phrases in sewing machine patent titles, rendering a list of patents that likely fit the dominant functional architecture. Divergent or unusual patents that break from the dominant functional architecture would not likely be found using this patent search process, as these unique patents would have a lower chance of relating to the most common sewing machine subsystems. Nonetheless, it is improbable that a significantly novel functional architecture emerged—and if it did emerge, it did not succeed (overtake the dominant functional architecture) because no other dominant functional architecture is observed in modern sewing machines.

### 4.2 Functional Stability Precedes Architectural Stability.

The data show that functional stability precedes architectural stability. The era of incremental functional change began after the era of ferment in the late 19$^{th}$ century, yet physical architecture has continued to change dramatically. Coincidentally, physical architecture is not necessarily an accurate representation of product functional innovation. Designs with perceived differences in physical architecture may have very similar functional architectures. This phenomenon is most evident during the development of the dominant design. Both in early and newer patents, two vastly different physical architectures often have nearly identical functional models. The difference is usually negligible when comparing patents within subsystems and only marginally more significant when comparing patents of complete machines from the era of ferment.

Figure 7 shows four examples of physical implementations of the feed mechanism subsystem, aligning with the functional model shown in part (**C**) of Fig. 1. Each patent has focused on improving the design of the feed mechanism in some different way, resulting in vastly different forms. Yet the parts of their functional models relating to the feed mechanism are identical, except for differences in control and use of electricity. In some cases, electrical energy is a means to generate control signals and provide mechanical energy to the system, but these differences are external to the dominant functional architecture. In particular, patent 8,850,999 (bottom right) has implemented a programmable mechanism for rotating the needle plate and feed dogs. The functional motif for control feed direction existed as early as 1851. In other words, the market's accepted the function (and functional architecture) of the control feed function even as inventors were experimenting with different ways to realize the functional architecture in physical form.

We conclude from this observation that functional stability long preceded stability in the component architectures of sewing machines. Throughout the 1900s inventors tinkered with the assemblage of components in pursuit of increased performance, ease of use, reliability, manufacturability, and decreased cost, all while operating within the dominant functional architecture established decades earlier. While these characteristics are important ways to innovate on the design and achieve commercial success, they are independent of the mechanical functionality of sewing machines that we focused on in this research.

### 4.3 New Forms of Design Competition After a Dominant Design Emerges.

Conventional dominant design theory states that once a dominant design emerges, firms compete on the cost of manufacturing. Our research suggests two other forms of competition. First, the results in Sections 4.1 and 4.2 demonstrate that manufacturers continue to compete on design: the design of components and their configuration to increase precise control and, to a lower extent, enhancements to the design of particular components. Contrary to the general prescription that manufacturers should compete on manufacturing cost after the emergence of a dominant design, these results show that sewing machine manufacturers continued to compete on the design of a sewing machine's components and subsystems after the emergence of a dominant design but within the framework of the dominant functional architecture.

A second more important finding on competition is that the existence of a dominant functional architecture allowed inventors to shift the basis of invention and innovation toward design solutions and functionality in sub-functions and subsystems rather than the entire product itself. This design strategy is revealed in the number and types patents in the modern era. By 1900, our patent search returned markedly decreased numbers of patents for complete machines; instead, the patents addressed specific subsystems (function motifs) of the sewing machine. Before a dominant functional architecture existed, design innovations across multiple sub-functions or subsystems were riskier and more challenging but necessary because the market still needed to learn which functional architecture would result in a successful machine. During the era of ferment, we observed patents concerning entire sewing machines from 1842 (patent US 2,466) and as late as 1899 (patent US 994,532). Once the dominant functional architecture is understood by a large enough portion of the industry, invention and innovation continue to occur albeit of a different character. Invention and innovation occur within sub-functions because the overall architecture is already understood. Inventors no longer have to consider and design for all functionality; instead, they only need to ensure that the sub-functions or subsystems will fit with the dominant functional architecture. They shift the basis of competition toward sub-systems. Thus, the design process becomes inherently hierarchically modular once a dominant functional architecture exists. This pattern has been observed in the cell phone industry. Cell phone manufacturers were less likely to engage in design innovation at the level of core technology once a dominant design (a design with a common set of features found in a product offered by multiple manufacturers) emerged [31]. Instead, they tended to add new features and functions that could integrate with the existing dominant functional architecture to serve different segments of markets.

## 5 Conclusion

This paper contributed a new approach to identifying a dominant design based upon a search for functional motifs that recur across multiple generations of a design for a product. We named the ensemble of functional motifs as the dominant functional architecture. The findings revealed that a dominant functional architecture could appear even before a dominant *physical* architecture is observed. The results therefore confirm the concept of technological

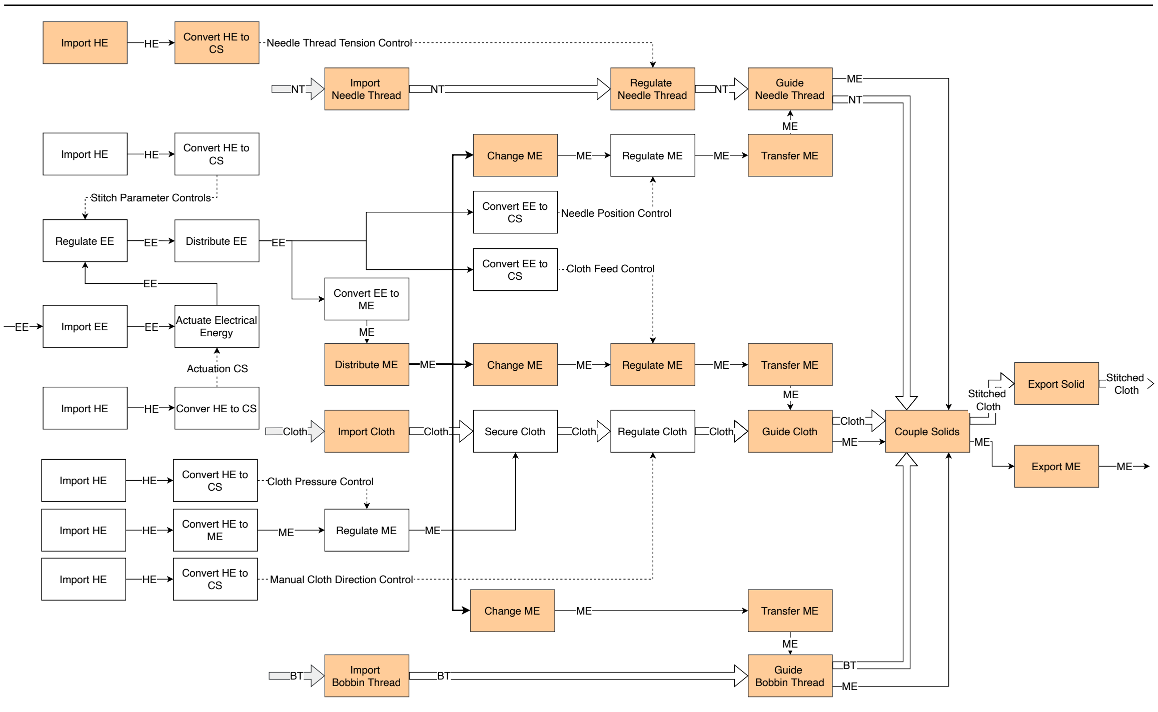


**Fig. 6 Functional model of modern sewing machine with shaded blocks matching patent 4,750**

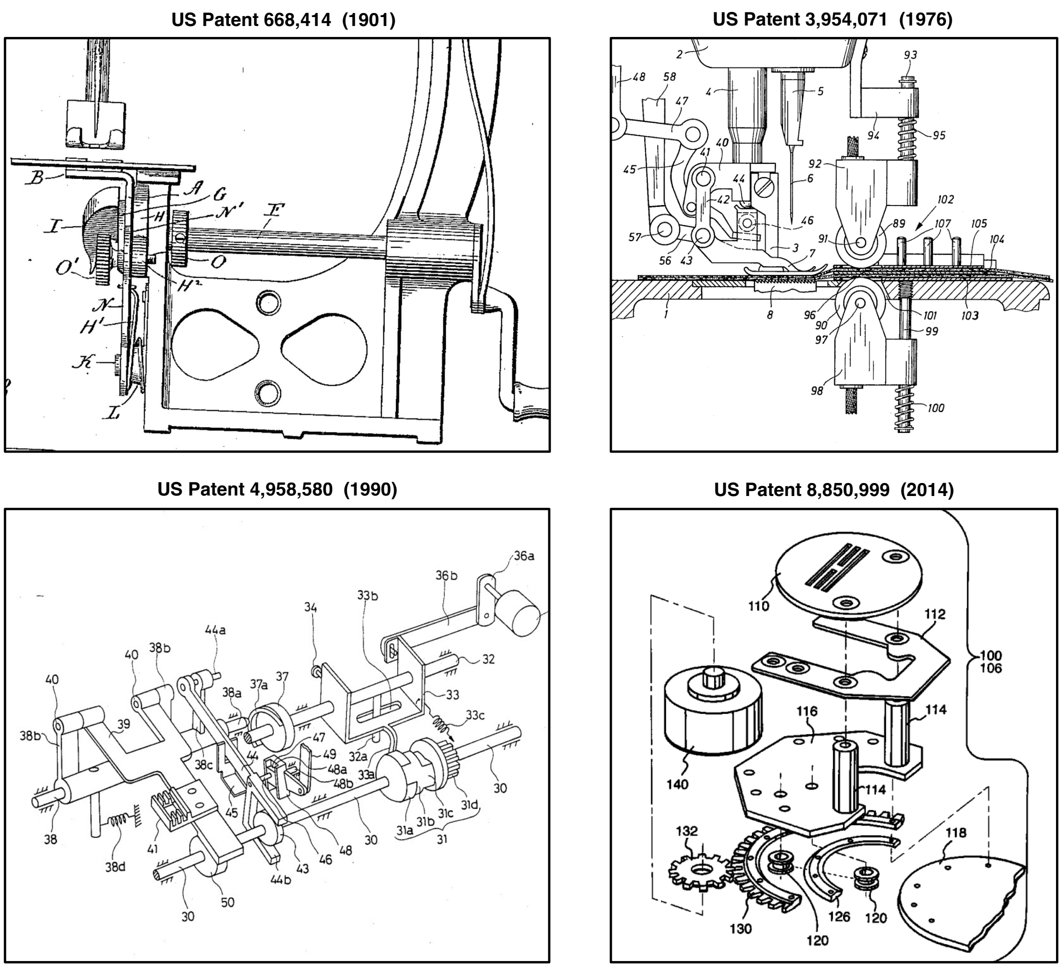


**Fig. 7 Four US sewing machine feed mechanism patents illustrating stark differences in physical architectures**

frames [13] as a more suitable way to define dominant designs rather than approaches based on physical architecture.

The findings are interesting in the context of emerging technologies such as autonomous vehicles. There does not yet exist a dominant functional architecture for autonomous vehicles, as evidenced by the myriad approaches to collecting and processing environmental information to drive the vehicle safely and the ambiguity surrounding the role of the passenger during operation. However, if a manufacturer did understand the dominant functional architecture for autonomous vehicles, the manufacturer could better understand which aspects of the design are important to compete on.

A limitation of this research is insufficient data to show more completely the evolution of the sewing machine in the era of ferment before Howe's patent. Likely, many important functional ideas leading up to patent 4,750 came from non-US patents. Important early non-US [19] patents include British patents 1,764 for a machine for "stitching, quilting, or sewing", 2,769 for a machine that made the chain stitch, and 3,708, a machine for stitching together several strands of rope, and the French patent to Barthélemy Thimonnier for a machine that could produce a chain stitch using a barbed or hooked needle.

The paper contributes to design theory in two crucial ways. First, in contrast to the design strategy recommendation that manufacturers should compete on manufacturing cost after a dominant design emerges, the findings show that manufacturers should compete on precision control. The lack of control signals appearing in the dominant functional architecture, and even during the era of ferment for the sewing machine, show an opportunity for control design to occur while design engineers resolve other functional issues. Given the low cost of microelectronic control systems, it is possible that this design strategy is already occurring in products since our data is based on a machine invented in the 1800s. Second, the findings suggest that firms should heed and know the dominant functional architecture because they can leverage it into adjacent product categories such as shoe-sewing devices, hat-making devices, and tennis racket stringing machines. All these machines are variants of a sewing machine in the foundational functional architecture. Finally, the findings have implications for mechanical design education. Current mechanical design education practice for functional modeling is to teach students to model a single product at a time [32] and then to use the model as the basis for new designs for the target product. Teaching students about dominant functional architectures for categories of products can help them design new types of machines for adjacent purposes just as the dominant functional architecture for sewing machines helped manufacturers in the textiles industry to design machines for, e.g., hat making.

In sum, this paper introduced the concept of a dominant functional architecture by modeling multiple generations of sewing machines to identify functional motifs that converged into a dominant design. This concept contributes to the theory base for explaining a technology life cycle.


## Acknowledgment

This material is based upon work supported by the National Science Foundation. Any opinions, findings, conclusions, or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation. We would like to also thank Mr. John DeJong, a volunteer for the Textile Collection at the National Museum of American History, for his contributions to aiding the research team in understanding early sewing machine patents and the USPTO patent database.

## Funding Data

- National Science Foundation Grant No. 2034448


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