Embodied Design
Cognition: Action-Based
Formalizations in
Architectural Design
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This paper frames design knowledge as formalizable physical actions that can more fully exploit future design tools and production methods. As computational design tools become more physically interactive and integrated into our environment we need new research frameworks to develop theories of physical design action as a form of knowledge. Symbolic theories of design knowledge traditionally frame design activity as a mental process and as a result researchers have not fully explored the potential for bodily-based computational design knowledge. We present an action-based design notation drawing inspiration from music performance theory to illustrate how this may impact design research. We discuss findings from situated cognition in cognitive science as an alternative framework for exploring and expanding design knowledge. We conclude with suggestions for future work in robotic-aided design cognition.
1. INTRODUCTION

In a world largely defined by digital processes that render knowledge to that which can be programmed on a computer, we must question what design knowledge is, where it exists, and how to expand upon and improve it. Is it in our minds? Is it in our bodies? Is it in our artifacts? Can it be embedded in our tools? Such questions lie at the intersection of design cognition and design computation, in other words—in how designers think about and do design in a formalized way.

Early theories of design cognition were not only based on metaphors of the mind as a symbol processor, but were constructed as and tested with symbol processors [1]. Theories of design thinking became defined by the very tools used to simulate design activity. This led to a design science [2] and research methods [3], [4] that framed design as a symbol manipulation process. As a result, we now have computational design tools that neglect and limit development of the embodied knowledge involved in designing. Embodied design knowledge may include the physical actions designers perform when sketching or model-making, the tacit feelings surrounding new ideas, or the social interactions in design environments. The mentalist perspective found in traditional design cognition excludes such experiences and is best summed up by Cross: “Asking ‘Can a machine design?’ is similar to asking ‘Can a machine think?’” [5]. We propose that design knowledge is more than thinking and symbol manipulation—it is doing, feeling, and interacting.

Alternative theories of human cognition such as Embodied or Situated Cognition are not limited by the symbolic representation required when building information-theoretic models. Instead, “Knowledge depends on being in a world that is inseparable from our bodies, our language, and our social history” [6]. This work explores what design knowledge can be if we think through our bodies instead of through the mental aid of our symbol processing tools.

1.1. Skill or knowledge? Cognitive offloading in digital design

Digital tools provide a clear starting point for finding evidence of a designer’s embodied knowledge because we can directly compare the symbolic description of a design activity with a non-symbolic description. For example, while the process of drawing a simple shape with a CAD tool can be symbolically described as text commands or algorithms, it can also be richly formalized through the physical motions of the body as it interacts with the tool (Figure 1).

These motions are bodily-based knowledge in action and can be considered separate from skill. Noë calls this “sensorimotor knowledge” through which we give structure to our bodily experience [8]. Sensorimotor knowledge was given its name by first framing the phenomenon as ‘cognitive
offloading’ (see [7] for in-depth discussion). An anecdotal example of cognitive offloading is found in memory retrieval. When attempting to remember a phone number, a person might raise up her hand and type out the number in space on an imaginary keypad. By doing this the memorization task has been ‘offloaded’ to the physical actions of typing the numbers, which may help in its recall. But in order to offload to the environment, the person must first know that it exists at their disposal.

Returning to our example above in Figure 1, let us consider what is cognitively offloaded when creating a circle with a CAD tool. When first learning how to draw a circle with a digital tool, the novice designer depends heavily on its symbolic descriptions such as the text commands, their sequential ordering, and the location of the keys on the keyboard. Over time, as the novice draws more and more circles, she relies less upon the symbolic descriptions for knowing how to create a shape and more upon her actions for simply ‘doing’ so. Framed this way, the knowledge needed for drawing a circle can be attuned to becoming aware of the sensations structuring movement, feeling, and seeing.

Imagine the embodied knowledge an experienced designer exhibits when designing an entire building. Our question becomes: is the expert one who memorizes more symbolic descriptions or one who exhibits more awareness of his movements and feelings? Described in these terms, the embodied knowledge of architectural designers can be likened to that of exceptional physical performers. We imagine design activity that is as generative as an improvisational jazz pianist, as exhilarating as a gymnast, and as precise yet graceful as a ballet dancer.

1.2. Schon’s limitations of digital computation

The traditional conception of design knowledge exemplified through current digital computation technologies continues to frame knowledge through symbolic representations, whether these are the CAD commands for drawing 2D shapes, or algorithms for parametrically arranging facades, or
BIM systems for project life-cycle analysis, e.g., see [9]. Schon presents this symbolic framing as a limitation of digital computation when he makes his observations of design as ‘local move experiments’. He writes, “Computers are unable - at least presently unable - to reproduce: the perception of figures or gestalts, the appreciation of qualities, the recognition of unintended consequences of moves” [10]. Schon is saying that our digital computation tools cannot account for, support, or enhance a large part of what goes on in design activity: how we are able to see something in a new way through a succession of seeing-moving-seeing.

1.3. Visual and physical computation

We suggest that the traditional focus on symbolic formalization has blinded researchers to the tacit dimensions [11] of design knowledge that Schon identified over 20 years ago. Stiny is one of the few who has seen this dimension and formalized it, although he discusses a limited example. He writes about Schon’s kind of seeing through his terms of “visual calculating” [12]. Shape grammars are his example of a non-symbolic formal system that engages the designer’s ability to see anew—to perform a visual interpretation on non-discrete elements such as lines and shapes. That the lines and shapes in Figure 2 can merge and break apart in an infinite yet solvable number of ways is what makes shape grammars a compelling example of a non-symbolic visual calculating system.

![Figure 2: What is the Shape composed of?](image)

What makes shape grammars formal is that they exploit a designer’s ability to not only see and recognize Schon’s ‘unintended consequences of moves’—in this case, new shapes—but more importantly they allow a designer to “actively use them as input for further computations” [13]. Within their Classic and Non-Classical Computation Framework, Knight and Stiny categorize this kind of visual computation as one that utilizes ‘non-classical representation’ [13]. Building from their framework and through theories found in embodied cognition we explore the idea that physical actions can be formalized in non-symbolic terms. If shape grammars are an example of a visual computation system that harnesses how designers see, can there be a physical computation system that harnesses how designers move?
1.4. Paper structure

In Section 2 we present the background to our work. This section will serve readers who are unfamiliar with the symbolic vs non-symbolic debate in design computation and cognition research. We first review theories and methods in design cognition and protocol analysis; we outline arguments from cognitive science that suggest knowledge is not limited to our ‘minds’; and we present recent applications found in human-computer interaction that demonstrate potential advancements for design tools. In Section 3 we show an action-based notation from music performance theory as an example of a non-symbolic system that formalizes bodily movement. In Section 4 we introduce our action notation and speculate on its potential impact on design cognition and computation. We then discuss how research in embodied cognition may provide a foundation for further developing bodily-based design knowledge. In Section 5 we outline future work including our early exploration into robotic tools for enhancing sensorimotor knowledge. Lastly, we provide a summary of contributions and offer our conclusions in Section 6.

2. BACKGROUND

2.1. Symbol processing in design protocol analysis

Design protocol studies have led to novel formalizations of the design process and have expanded computational models of design knowledge [14]. Protocol studies commonly represent the design process through coding schemas and segmentation, e.g., [15]; or as descriptive narratives of the design process made through video analysis, e.g., [16]; or from thoughts voiced by the designer known as the voice-out-loud or concurrent protocol method [17]. Some studies do account for the physical actions designers make, e.g., sketching, looking, and gesturing [18], however these actions are neither hypothesized to impact the design process nor constitute a kind of design knowledge.

These symbolic approaches to formalizing design activity can be traced back to theories of cognition and computation put forth by Herbert Simon and others. Particularly illuminating is a series of articles published in a special issue of Cognitive Science on Situated Activity theory, an early articulation of embodied cognition [19-23]. Beginning with an article by Vera and Simon, the authors present cases for whether or not knowledge is fundamentally symbolic in nature or whether it is contextually situated. Greeno and Moore sum up the central question underlying both sides:

“The question, then, seems to be something like this: whether (1) to treat cognition that involves symbols as a special case of cognitive activity, with the assumption that situativity is fundamental in all cognitive activity, or (2) to treat situated activity as a special case of cognitive activity, with the assumption that symbolic processing is fundamental in all cognitive activity.” [20]
Vera and Simon clearly take the symbol-processing side arguing that perception, thinking, and action can be described definitively in terms of abstract symbols, or information:

“Sequences of actions can be executed with constant interchange among (a) receipt of information about the current state of the environment (perception), (b) internal processing of information (thinking), and (c) response to the environment (motor activity).” [19]

In Vera and Simon’s theory a designer can be modeled as an input/output device with a mind in between that operates like the central processor of a digital computer. Based on this hypothesis, one of the key challenges for design protocol analysis has become an algorithm development problem as a method for formalizing the cognitive steps involved in the ‘internal processing of information’.

More recent work in design protocol analysis has expanded symbolic formalization to include the external, context-specific conditions of design activity. Smith and Gero discuss this in terms of ‘situatedness’ whereby design is framed as an interaction between constantly changing variables in a dynamic solution space [24]. An example formalization from design protocol analysis based on this symbolically situated approach is the Situated Function-Behavior-Structure framework [25].

2.2. Situating embodied cognition in design activity

Theories of embodied cognition can further expand our conception of design knowledge by questioning the symbol-processing model of cognition. However, there is still much debate surrounding what exactly embodied cognition means and there are many competing names it goes by: situated cognition [26], enactive cognition [8], and extended and distributed cognition [27], to name a few. Nemirovsky and Ferrara write:

“Embodied cognition rejects the notion that behind perceptual-motor activity there is a ‘mind’…Whatever we can recognize as rational, rule-based, or inferential, is fully embedded in our bodily actions; perception and motor activity do not function as input and output for the ‘mental’ realm; what we usually recognize as mental are inhibited and condensed perceptual-motor activities that do not reach the periphery of our nervous system.” [28]

Anderson states that the central focus of work in embodied cognition is the symbol-grounding problem which questions where symbols acquire meaning for humans. Anderson writes that symbols “must ultimately ground out in [terms of] the agent’s embodied experience and physical characteristics” [29]. In other words, while we can and do use symbols to represent and communicate knowledge, these symbols depend on our bodies and the physical environment for us to make sense of them.

From the embodied cognition perspective, it is relevant to ask what
designers do with their bodies in their environment during design activity. They are sitting at desks, typing on computers, standing around laser cutters, handling tools, manipulating materials, working alone, gathering in small groups, and so forth. According to theories of embodied cognition these seemingly ordinary everyday activities are ripe with generative potential for shaping a design outcome.

The impact of embodied cognition is just beginning to be felt in design research. Although many have speculated about integrating new theories of cognition to reframe the design process [24], [30-31], little work has been done to empirically test the theories, let alone to implement formal systems. Most work simplifies the design task in order to formalize the embodied activities. Knight and Stiny for example develop a formalization of the physical actions involved in craft-making activities such as knot-tying. In their view, design, even in computationally aided processes, is not an intellectual activity but rather “a kind of making itself, an activity that demands perceptual, bodily engagements with the materials of the world” [32]. Maher et al. present how physical interaction with programmable toys—Sifteo Cubes—leads to more creative solutions in simple word-play tasks. Using protocol analysis they investigate how gestures affect creative interaction by increasing the affordances of the programmed cubes [33]. Smithwick and Sass categorize three different types of physical actions involved in assembling digitally fabricated structures: interfacing—the configuration state of the hand in relation to material components; interacting—the progression of interface states over time; and interchanging—transformations between the hand, the components, and the work environment [34].

2.3. Human-computer interaction

Although most work in embodied cognition is theoretical or empirical there are project-based research examples demonstrating practical tools that exploit the physical interactions between users and tools [35]. Recent work from the field of Human-Computer Interaction (HCI) demonstrates embodied cognition theories applied in prototyping tools. For an overview of HCI from an architectural computation perspective, see [36]. Some tool developers situate the control and design interface of digital fabrication tools such as CNC routers directly on the machine and allow for real-time control of the cutting bit through motion tracking technologies [37-38]. Zoran and Paradiso constructed a handheld Dremel-like digital sculpting tool called FreeD enabling a user to more directly engage with the sculpting material through the aid of computational feedback to correct movement errors based on a digital design [39]. Braumann and Cokcan have developed gestural interfaces for controlling robotic arms using the motion of the body [40]. They explore physical computing technologies such as Arduino microcontrollers and Kinect cameras to develop programming platforms for
novice designers to more intuitively and directly control robotic motion.

Such projects demonstrate how digitally integrated physical tools can engage the designer’s body by means of haptic, motion, and infrared sensors. As robotics and other environmental computing technologies are subsumed into the architectural design process, designers and design researchers will need theories of embodied interaction to frame the technical development in meaningful and productive ways.

3. A NON-SYMBOLIC NOTATION FOR MUSIC PERFORMANCE

Before we present our action-based notation for design, we would like to present a related piece of work from the field of music performance research. We find this comparison inspirational and useful upon many levels. For the reader who is also a musician, we think this comparison will provide novel insight into the creative undercurrents found in both a musician’s performance and a designer’s actions. Many researchers have proposed metaphors relating music to architecture; however, we propose a more literal comparison: Designers and musicians alike interact with a wide range of tools to develop and express conceptual ideas which result in physical phenomena. It is also the case that formal symbol systems are used extensively in music composition and design computation to represent and communicate ideas. By considering how musicians use their bodies to interpret formal systems, designers may learn embodied computational strategies for performing design activity.

Below is a study from the *Music Performance Research* journal of German composer Helmut Lachenmann’s action-based notation developed for his 1969 piece for solo cello, *Pression* (Figure 3) [41]. Orning describes Lachenmann’s action notation as:

“A reversal of traditional hierarchies, prioritizing the performance over the musical text. Lachenmann shifts the focus from the score as musical text to the action embodied in performance. This shift in compositional focus calls for a complementary shift in analytical focus.” [41]
3.1. A hidden dimension between the notes

In Lachenmann’s notation, the musical notes as traditionally represented (half notes, quarter notes, etc.) still exist and function accordingly; however, the notation reveals and prioritizes a ‘hidden dimension’ between the notes that the musician can exploit. At an intuitive level to the experienced musician this hidden dimension is very real: music happens ‘off the page’ and the notes as a formal system are there only as music theory’s best approximation for delivering a desired aural effect. What Lachenmann’s notation does is formalize how the musician might physically interpret and perform this musical dimension through different types of lines (zig-zags, dotted lines, sloping lines, horizontal arrows, etc.) and graphics (figurative drawings of hands and cello parts) (Figure 3). For example, the zig-zag could be performed as the shape of the motion a musician makes with his hand, and the schematic drawing of the fret board identifies where actions take place on the instrument.

What makes Lachenmann’s system of lines and graphics non-symbolic is that the musician’s interpretation is defined only by his body in action rather than with a predetermined set of motion paths. In other words, every interpretation in time will be equally unique and correct. With
Lachenmann’s action-based notation we have an example of a formalization that expands the world of pre-determined symbolic representation without sacrificing the structure of a framework that makes it possible to share, preserve, and improve an active form of knowledge. Is this possible in the designer’s world?

4. A NON-SYMBOLIC FORMALIZATION FOR DESIGN

Our formalization shifts the traditional hierarchies found in design cognition and computation (which place priority on symbolic steps and processes as the foundation of creative work) in much the same way that traditional hierarchies in music place priority on the musical composition as the creative work. To illustrate our action-based formalization we return to the example of drawing a shape with a CAD tool.

To more clearly convey our formalization we contrast it with a symbolic formalization of the same exercise of drawing a circle in AutoCAD (Table 1). The primary purpose in developing this example is to reveal that even within the simple act of drawing a circle with a CAD tool the traditional conception of design knowledge is blind to how a designer uses his body interactively to express and develop design ideas (Figure 4). As such, this formalization should be read as an illustrated thought experiment to ground the discussion.

Figure 4: Detail of articulated hand movements when typing the word ‘circle’ in AutoCAD.
<table>
<thead>
<tr>
<th>Symbolic Formalization</th>
<th>Action-Based Physical Design Notation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Initialize the Command</strong></td>
<td><img src="image" alt="Diagram of hands and notations" /></td>
</tr>
<tr>
<td>1. With fingers, type 'c-i-r-c-l-e' using keyboard</td>
<td><img src="image" alt="Diagram of hand gestures and notations" /></td>
</tr>
<tr>
<td>2. Hit the 'space bar' key on keyboard</td>
<td><img src="image" alt="Diagram of hand gestures and notations" /></td>
</tr>
</tbody>
</table>

**Define the center point**

| 3. Position mouse with hand to locate center point | ![Diagram of mouse and center point](image) |

**Define the radius length**

| 5. With hand holding mouse, drag mouse away from center point to designate length of radius | ![Diagram of mouse and radius](image) |
| 6. Using index finger, tap left mouse button to set radius and complete the circle command | ![Diagram of mouse and radius](image) |

▲ Table 1: Comparison between a symbolic formalization with an action-based notation for drawing a circle with a CAD tool.
The formalization in Table 1 is to be read from left to right as one might read musical notation. In Step 1, the horizontal dashed line represents the line made by the fingers as they rest on the ‘home row’ of a standard computer keyboard. The up and down arrows indicate the order, direction, and quality in which the designer can move his fingers as they strike the keys to spell out the word ‘circle’. For example, in Step 1 the left-most black down arrow indicates to the designer that using his left index finger (labeled 1L) he should strike the ‘C’ key on the keyboard. Next, the designer should use his middle finger on his right hand (labeled 2R) to strike the ‘I’ key on the computer keyboard. The remainder of Step 1 in Figure 3 follows accordingly. Steps 2-6 in Table 1 complete the circle drawing exercise with notation for using a computer mouse.

Most importantly, our action notation suggests potential for harnessing the physicality of a designer’s movements. This is the ‘hidden dimension’ we discussed in Section 3. For example, the timing between movements (Figure 4A), the amount of force used (Figure 4B), and duration of striking (Figure...
4C) can now be considered as meaningful engagement between the designer and the tool. What these physical actions mean and how they support and structure the design process is an open question that needs exploring.

4.1. Discussion: What can designers learn from the physical actions of Tetris players, mathematicians, and dancers?

As a thought experiment, our formalization opens up an avenue of investigation overlooked in design research: how designers use their bodies to explore novel solutions. However, where and how do we draw the limits of design as an interactive activity? Design is certainly more than the motions of typing AutoCAD commands on a keyboard, but should we also consider a student’s posture as part of his design thinking? What about the gestures he makes while presenting his project to critics or the way he constructs physical models with his hands? Are such superfluous actions connected with design knowledge? Research from psychology suggests a relationship exists between spatial thinking and gesture production [42, 43]. As we identified above, designers perform many different types of physical actions for many different reasons in many different settings. How can we make sense of these intuitive and tacit dimensions of designerly interaction with the world?

Theories developed from work in embodied cognition may help structure the study of physical action in the context of design research. Kirsh and Maglio developed the theory of Epistemic Action which says that not all actions are for pragmatic goal-oriented purposes. They witnessed expert Tetris players utilize “physical actions [to] make mental computation easier, faster, or more reliable” [44]. The players would perform seemingly extraneous physical actions during game play, such as overly rotating zoids or translating zoids across the entire screen, taking them further away from achieving the immediate goal at hand—dropping the zoids into rows. But ultimately, claim Kirsh and Maglio, such actions “make it easier for [Tetris players] to attend, recognize, generate and test candidates, and improve execution” [44]. Do designers perform similarly extraneous actions that help them make design decisions?

Much of design knowledge, however, is conceptual rather than practical. How does bodily action support conceptual thinking? Recent research in the learning sciences investigates the connection between physical action and learning mathematical concepts. Goldin-Meadow and Beilock demonstrate how specific types of gestural actions enhance the ability to learn abstract concepts [45]. Martin and Schwartz demonstrate how interaction with physical objects like Montessori Blocks help children to learn mathematical concepts that they were unable to learn through mental representation only [46]. These examples show how gesturing and physical interaction aid in communicating abstract ideas and in helping students think through conceptual problems.
Although Cross is concerned with equating the bodily intelligence of dancers with that of the creativity of inventors [5], new research is expanding the significance of kinesthetic intelligence in relation to our imaginative powers. In recent work, Kirsh studies the use of abstract bodily motions called ‘marking’ in professional dancers’ practice routines [47]. When learning new choreographies, instead of practicing the steps and phrases ‘full out’, more successful dancers devise limited bodily actions to simulate the full maneuvers. What this suggests is that contrary to the traditionally defined role of the body as an output device of internal thought, the body serves as a physical extension of thought capable of generating structure upon which new shapes, orientations, and sequences of thought are possible.

5. FUTURE WORK: FORMALIZING EMBODIED DESIGN KNOWLEDGE FOR EXPLORING ROBOTIC INTERACTION

What these examples show is the opportunity design researchers have to explore and expand conceptions of design knowledge by considering the body as an active and multi-functioning participant in the design process. What are the epistemic actions designers perform? Are such physical actions related to the reflective actions Schon describes in ‘seeing-moving-seeing’ [48]? What are the conceptual problems designers communicate through gesture or explore through interaction with physical materials? Do designers construct prototype models similar to how dancers perform marking as a strategy for scaffolding creative thought? What new tools can we devise to harness this action-based embodied knowledge?

One of the most exciting and potentially fruitful applications of these questions in design research is in developing robotic-aided design cognition. We have begun investigating this area by conducting empirical studies on fundamental physical actions designers perform in support of creative problem solving tasks. We compare and contrast these actions with how a robotic arm may be programmed to conduct similar tasks. These are basic grasping and displacement actions used to manipulate physical objects including: pushing and pulling blocks on 2D surface (Figure 6A); picking, placing and stacking blocks in 3D patterns (Figure 6B); assembling interlocking components to form simple planar assemblies (Figure 6C); and assembling interlocking components to form complex curved structures (Figure 6D).

By studying these basic physical actions we can develop a fundamental framework of the embodied knowledge designers deploy in design activity. Although much research has been conducted on the automation of translating digital models into physical constructions with the aid of digital fabrication tools [49] and recently with robotic tools [50], little is still known about the designer’s sensorimotor knowledge to interact with material objects when developing design ideas. Questions still remain: Do
expert designers interact differently than novices? Can robotic tools enhance our embodied cognitive knowledge through demonstration and interaction? Can we formalize student-teacher interactions to integrate robotics into the design studio?

6. CONCLUSION

The central question we have explored in this paper asks: Where does design knowledge exist? Is it an intellectual activity within the mind or is design knowledge embodied in our finger tips or does it extend out into the world as we interact with it? Such questions have been asked in many fields of research including cognitive science, artificial intelligence, and philosophy of mind with many different answers. As we have shown, traditional theories of design cognition have held the narrow view that design is an information or symbol-processing activity. One contribution of our work has been to question this view by exploring theories of embodied cognition and discussing examples of bodily-based knowledge in other creative human activities.

We have also contributed an illustrated thought experiment of how embodied theories of cognition may provide insight into new forms of design knowledge. We use a novel example from music performance research to highlight a tacit dimension which exists in between pre-defined symbols, whether they are musical notes or automated CAD commands.

At the same time, we acknowledge that design researchers cannot exist in the tacit dimension alone. New technologies open the door for further research and expansion of design knowledge. Similar to how digital computation technologies defined the early research frameworks of design cognition, physical computation technologies such as integrated electronics and robotic tools are poised to challenge traditional notions of design cognition. We propose that theories of embodied cognition can give design
researchers a structure for the endeavor ahead of us. Stiny asks, “How would calculating be different if Turing was an artist or designer and not a logician?” Instead of calculating by counting, Turing would have calculated by seeing, says Stiny [51]. We ask: what if Stiny was a musician or dancer? Would he calculate by performing physical actions and interacting with the world?

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