Artificial intelligence has a long and rich history in the field of architecture. Building upon this history, we clarify the term adaptive and its use within the field. This allows us to explore the application of adaptive systems to architectural design through the prototyping of an adaptive solar envelope (ASE). The building envelope was chosen because it is a common place to address issues of energy performance and occupant comfort and thereby offers an ideal scenario in which to explore the negotiative potential of adaptive systems in architecture. The ASE prototype addresses issues of distributed shading, power generation through integrated thin film photovoltaics, and daylight distribution. In addition, building envelopes, being the most publicly visible part of a building, play an important role in the aesthetic result of a design. Therefore, conceiving buildings as dynamic systems with the ability to adapt to the fluctuating environments in which they exist opens new aesthetic possibilities for designers. We also present examples of student work created during workshops based on the theme of integrating adaptive distributed systems into architectural design. We argue that with presently available technology and an increased exposure of architecture students and practitioners to adaptive design techniques, adaptive architectures will soon become a regular element of the built environment.
1 INTRODUCTION

As Gordon-Park wrote in the forward to An Evolutionary Architecture, “the role of the architect here, I think, is not so much to design a building or city as to catalyze them; to act so that they may evolve” (Frazer 1995). This sentence has reverberated through the architecture world for close to three decades, inspiring architects to design from a systems perspective. While the idea that an architecture agent can be seen as an intelligent system is still science fiction for some, it has become daily practice for many. And while this quote from Paul is often cited as a root of contemporary digital architecture, the ideas embedded in Paul’s statement predate the work of John Frazer’s Diploma Unit 11 at the Architectural Association.

Previous to leading Diploma Unit 11, John and Julia Frazer worked as consultants for Cedric Price on his Generator project (1978–80). They helped Price develop digital and physical models of a reconfigurable architecture. The core concept of the project was that the architecture could be reprogrammed by its users to suit their desires. In addition, the architecture could suggest novel configurations on its own. Because of this self-motivated reconfiguration by the architecture, there could be a conversation, so to speak, between occupant and architecture, each influencing the other (Hue et al. 2002).

While the scale of execution conceived by Price for the self-reconfigurable architecture of the Generator project was unprecedented, many of the core concepts had been previously developed by Nicholas Negroponte within the Machine Architecture Group at MIT (Negroponte 1970). Specifically, Negroponte’s SEEK project (1970) had physically explored the idea of a self-reconfigurable architecture, but on a smaller scale than that proposed by the Generator project. SEEK combined a three-axis CNC robotic gripper with a set of small metal cubes and a small population of gerbils. As the inherently curious gerbils neared the metal cube environment, they bumped and moved the cubes. The robotic arm would straighten those cubes that had been rotated slightly from their original position, or realign them in their new location if they had been significantly displaced. Over time, this conversation between the gerbils and the robotic gripper evolved the physical environment (Negroponte 1975).

Negroponte’s work was also based on the ideas of his predecessors, and the previously mentioned people and projects represent only a small fraction of the long and rich history of integrating artificial intelligence and robotics into architecture. This history includes the works of Brooks, Eastman, and Rabinovich, among others (Fox 2010; Fox and Kemp 2009). While these forward-thinking individuals developed many concepts between the 1960s and early 1970s, it was not until the mid-1990s that computational power became affordable enough for physical exploration of these concepts to be widely available to students and practitioners of architecture. An increase in accessibility and affordability of microprocessors, such as the Arduino prototyping environment (Arduino 2012), has produced during two weeklong bachelor-level design workshops on the topic of ASE design. Section 3 describes the development of the 1:1 scale prototypes of the adaptive solar envelope (ASE), and highlights some of the student work produced during these weeklong bachelor-level design workshops on the topic of ASE design. Section 4 concludes the paper.

2 ADAPTIVE DISTRIBUTED ARCHITECTURAL SYSTEMS

2.1 On Adaptivity

Our understanding of an adaptive system is very specific and goes beyond the typical architectural notion of preprogrammed motion, termed kinetic, or systems that move based on sensor readings, termed responsive. Responsive systems are often referred to as being adaptive because they execute an action due to a certain sensor input, e.g., if the light level drops below 500 lux, turn the light on. In terms of a control system, this is a simple control law, and there is no adaptation. However, if over time this control law enables it to “if the light level drops below 472 lux, turn the light on,” i.e., the threshold level is changed without explicit human reprogramming, then we speak of an adaptive control system. Note that the responsiveness is still there, but in addition, adaptive control allows the automatic reprogramming of the responsiveness. We will employ this notion of adaptive for the remainder of this paper.

Adaptivity in architecture allows buildings to change their behavior in response to real-world events as opposed to preconceived assumptions, and therefore offers context-appropriate performance. One contemporary issue in architecture that can be addressed through the integration of adaptive design strategies is the negotiation of building energy performance and occupant desires. In fact, improving building energy performance can and should be done in a way that does not have negative consequences for building occupants, e.g., using set points based on mean values for comfort rather than the occupant’s actual desires. Ideally, the systems could learn through user interaction and thereby adapt their behaviors to the desires of the occupant(s) over time. A system would be free to optimize itself for energy performance when the space is unoccupied, or could even nudge an occupant toward “greener” habits by teaching the boundaries of what the occupant is willing to accept as comfortable. In essence, it would be an ongoing dialogue between occupant(s) and building, navigating their sometimes shared and sometimes contradictory desires. This acceptance of desire to the building is legitimized, as it helps us to conceptualize the building and “understand” its past or future behavior (McCarty 1979).

To achieve this type of adaptivity, we propose to use algorithms from the field of machine learning, specifically reinforcement learning (RL) algorithms. A detailed description is beyond the scope of this paper, and the interested reader is referred to standard textbooks (Mitchell 1997; Sutton and Barto 1998). Simply put, an RL algorithm finds the control law that optimizes balances different goals through interaction with its environment. This happens similarly to how humans learn or pet animals are trained, and can be generally referred to as a trial-and-error approach (see Figure 1). In response to a certain state of the environment, the system takes an action that it assumes appropriate. Upon completion of the action, it receives a reward representing the goodness of its action, which is then used to update its knowledge of the environment. When presented with a similar situation, the system can now use this updated knowledge to make a better decision toward its goal of maximizing the rewards and thereby finding the optimal control law. However, if over time this control law enables it to “if the light level drops below 472 lux, turn the light on,” i.e., the threshold level is changed without explicit human reprogramming, then we speak of an adaptive control system. Note that the responsiveness is still there, but in addition, adaptive control allows the automatic reprogramming of the responsiveness. We will employ this notion of adaptive for the remainder of this paper.

Adaptivity in architecture allows buildings to change their behavior in response to real-world events as opposed to preconceived assumptions, and therefore offers context-appropriate performance. One contemporary issue in architecture that can be addressed through the integration of adaptive design strategies is the negotiation of building energy performance and occupant desires. In fact, improving building energy performance can and should be done in a way that does not have negative consequences for building occupants, e.g., using set points based on mean values for comfort rather than the occupant’s actual desires. Ideally, the systems could learn through user interaction and thereby adapt their behaviors to the desires of the occupant(s) over time. A system would be free to optimize itself for energy performance when the space is unoccupied, or could even nudge an occupant toward “greener” habits by teaching the boundaries of what the occupant is willing to accept as comfortable. In essence, it would be an ongoing dialogue between occupant(s) and building, navigating their sometimes shared and sometimes contradictory desires. This acceptance of desire to the building is legitimized, as it helps us to conceptualize the building and “understand” its past or future behavior (McCarty 1979).

To achieve this type of adaptivity, we propose to use algorithms from the field of machine learning, specifically reinforcement learning (RL) algorithms. A detailed description is beyond the scope of this paper, and the interested reader is referred to standard textbooks (Mitchell 1997; Sutton and Barto 1998). Simply put, an RL algorithm finds the control law that optimizes balances different goals through interaction with its environment. This happens similarly to how humans learn or pet animals are trained, and can be generally referred to as a trial-and-error approach (see Figure 1). In response to a certain state of the environment, the system takes an action that it assumes appropriate. Upon completion of the action, it receives a reward representing the goodness of its action, which is then used to update its knowledge of the environment. When presented with a similar situation, the system can now use this updated knowledge to make a better decision toward its goal of maximizing the rewards and thereby finding the optimal control law. However, if over time this control law evolves to “if the light level drops below 472 lux, turn the light on,” i.e., the threshold level is changed without explicit human reprogramming, then we speak of an adaptive control system. Note that the responsiveness is still there, but in addition, adaptive control allows the automatic reprogramming of the responsiveness. We will employ this notion of adaptive for the remainder of this paper.

Adaptivity in architecture allows buildings to change their behavior in response to real-world events as opposed to preconceived assumptions, and therefore offers context-appropriate performance. One contemporary issue in architecture that can be addressed through the integration of adaptive design strategies is the negotiation of building energy performance and occupant desires. In fact, improving building energy performance can and should be done in a way that does not have negative consequences for building occupants, e.g., using set points based on mean values for comfort rather than the occupant’s actual desires. Ideally, the systems could learn through user interaction and thereby adapt their behaviors to the desires of the occupant(s) over time. A system would be free to optimize itself for energy performance when the space is unoccupied, or could even nudge an occupant toward “greener” habits by teaching the boundaries of what the occupant is willing to accept as comfortable. In essence, it would be an ongoing dialogue between occupant(s) and building, navigating their sometimes shared and sometimes contradictory desires. This acceptance of desire to the building is legitimized, as it helps us to conceptualize the building and “understand” its past or future behavior (McCarty 1979).

To achieve this type of adaptivity, we propose to use algorithms from the field of machine learning, specifically reinforcement learning (RL) algorithms. A detailed description is beyond the scope of this paper, and the interested reader is referred to standard textbooks (Mitchell 1997; Sutton and Barto 1998). Simply put, an RL algorithm finds the control law that optimizes balances different goals through interaction with its environment. This happens similarly to how humans learn or pet animals are trained, and can be generally referred to as a trial-and-error approach (see Figure 1). In response to a certain state of the environment, the system takes an action that it assumes appropriate. Upon completion of the action, it receives a reward representing the goodness of its action, which is then used to update its knowledge of the environment. When presented with a similar situation, the system can now use this updated knowledge to make a better decision toward its goal of maximizing the rewards and thereby finding the optimal control law. However, if over time this control law evolves to “if the light level drops below 472 lux, turn the light on,” i.e., the threshold level is changed without explicit human reprogramming, then we speak of an adaptive control system. Note that the responsiveness is still there, but in addition, adaptive control allows the automatic reprogramming of the responsiveness. We will employ this notion of adaptive for the remainder of this paper.
of the components can be defined by user control or by a solar tracking behavior, or it can run in
a preprogrammed series of movements. The basic module of the ASE consists of a pair of stacked
servos and a microcontroller, and a solar thin film cell. The various elements of the basic module
are shown in Figures 5a–c. The stacked servo pair is mounted with pan-tilt brackets, giving the
module two degrees of rotational freedom, shown in Figures 6a and 6b. Figure 6c shows the
hemispherical operational boundary allowed by the setup. This freedom of rotation gives the
components the flexibility to track solar movements throughout the course of the day/year, which
can increase power production from photovoltaic systems by 35–40 percent (Abdallah and Nijmeh
2004).

The initial inspiration for our solar tracking module came from Valentino Braitenberg’s
Braitenberg described how through building simple sensor/actuator relationships “behaviors” could
be observed in manmade artifacts. One of the vehicles developed conceptually in the book used a
pair of light sensors to drive a pair of motors. As shown in Figure 7, depending on the relationship of
the wiring between the sensors and the motors the vehicles would express a “light loving” behavior.

3 ADAPTIVE DISTRIBUTED DESIGN
3.1 Physical Prototype
The Adaptive Solar Envelope (ASE) 1:1 scale prototype, shown in Figure 4a, was developed to explore
multiple aspects related to the implementation of adaptive distributed systems in built architecture.
As shown in Figure 4a, this project is highly interdisciplinary, integrating concepts of renewable
carbon, user interaction, adaptive control, and architectural design.

The prototype is 2.25 m high by 1.25 m wide and consists of 36 modular components. The movement
ingenue, acting as a buffer between interior and exterior environments, offers an ideal medium
through which an architecture and an occupant may converse. The envelope is also a highly important
area in terms of architectural design, as it is, in essence, the public face of a building. As shown
in Figure 2a–c, the envelope can mitigate solar insolation, thereby offering reductions in heating/
cooling loads, and improve distribution of daylight.

If we imagine that a facade element has a certain behavior—for example, solar tracking—then it can
act independently to optimize shading or solar harvesting potential. In addition to acting autonomously,
the module could be clustered into small groups. Likewise, groups of clustered modules can relate to a
window or particular interior spaces. These, in turn, if proliferated, could make up the facade or entire
envelope of a building (see Figure 3). This distributed approach can be deployed at various scales and
locations depending on the goal of the system. We believe that a distributed approach allows for local
variation in response to internal and external factors, and thereby offers the highest probability of
negotiating conflicting goals. The result of such a system also produces a visually dynamic building
envelope, which expresses the negotiation between building and occupant desires.

Enveloping various states of building envelope components: a) closed state, reflecting solar radiation; b) open state, allowing views and bouncing daylight into the interior; c) solar tracking state, optimizing for maximum power generation if PV elements are integrated; and d) “mixed state,” allowing multiple functions to be fulfilled simultaneously. It is the flexibility of the mixed state that gives the system the ability to adapt to user desires.

Scales of distribution: a) single component scale; b) cluster scale; c) window scale; and d) building scale. Varying degrees of autonomy and control can be applied at various scales.

The initial inspiration for our solar tracking module came from Valentino Braitenberg’s
Braitenberg described how through building simple sensor/actuator relationships “behaviors” could
be observed in manmade artifacts. One of the vehicles developed conceptually in the book used a
pair of light sensors to drive a pair of motors. As shown in Figure 7, depending on the relationship of
the wiring between the sensors and the motors the vehicles would express a “light loving” behavior.

The Adaptive Solar Envelope (ASE) 1:1 scale prototype, shown in Figure 4a, was developed to explore
multiple aspects related to the implementation of adaptive distributed systems in built architecture.

As shown in Figure 4a, the project is highly interdisciplinary, integrating concepts of renewable
carbon, user interaction, adaptive control, and architectural design.

The prototype is 2.25 m high by 1.25 m wide and consists of 36 modular components. The movement
of the components can be defined by user control or by a solar tracking behavior, or it can run in
a preprogrammed series of movements. The basic module of the ASE consists of a pair of stacked
servos and a microcontroller, and a solar thin film cell. The various elements of the basic module are shown in Figures 5a–c. The stacked servo pair is mounted with pan-tilt brackets, giving the module two degrees of rotational freedom, shown in Figures 6a and 6b. Figure 6c shows the hemispherical operational boundary allowed by the setup. This freedom of rotation gives the components the flexibility to track solar movements throughout the course of the day/year, which can increase power production from photovoltaic systems by 35–40 percent (Abdallah and Nijmeh 2004).

The initial inspiration for our solar tracking module came from Valentino Braitenberg’s
Braitenberg described how through building simple sensor/actuator relationships “behaviors” could
be observed in manmade artifacts. One of the vehicles developed conceptually in the book used a
pair of light sensors to drive a pair of motors. As shown in Figure 7, depending on the relationship of
the wiring between the sensors and the motors the vehicles would express a “light loving” behavior.

3 ADAPTIVE DISTRIBUTED DESIGN
3.1 Physical Prototype
The Adaptive Solar Envelope (ASE) 1:1 scale prototype, shown in Figure 4a, was developed to explore
multiple aspects related to the implementation of adaptive distributed systems in built architecture.

As shown in Figure 4a, this project is highly interdisciplinary, integrating concepts of renewable
carbon, user interaction, adaptive control, and architectural design.

The prototype is 2.25 m high by 1.25 m wide and consists of 36 modular components. The movement
of the components can be defined by user control or by a solar tracking behavior, or it can run in
a preprogrammed series of movements. The basic module of the ASE consists of a pair of stacked
servos and a microcontroller, and a solar thin film cell. The various elements of the basic module are shown in Figures 5a–c. The stacked servo pair is mounted with pan-tilt brackets, giving the module two degrees of rotational freedom, shown in Figures 6a and 6b. Figure 6c shows the hemispherical operational boundary allowed by the setup. This freedom of rotation gives the components the flexibility to track solar movements throughout the course of the day/year, which can increase power production from photovoltaic systems by 35–40 percent (Abdallah and Nijmeh 2004).

The initial inspiration for our solar tracking module came from Valentino Braitenberg’s
Braitenberg described how through building simple sensor/actuator relationships “behaviors” could
be observed in manmade artifacts. One of the vehicles developed conceptually in the book used a
pair of light sensors to drive a pair of motors. As shown in Figure 7, depending on the relationship of
the wiring between the sensors and the motors the vehicles would express a “light loving” behavior.
In order to explore the aesthetic potential of custom solar thin film geometries, we selected a semiregular tiling pattern, shown in Figure 9, to develop into the built prototype. The pattern produces a high degree of visual interest through the use of only two repeating geometries. The semiregular tiling pattern was also responsible for defining the underlying support structure, as the center point of each module defined a connection location between it and the support structure. Because the components move independently of each other, and in response to varying internal and external environmental influences, complex surface patterns can emerge without the need for entirely nonstandard production of components.

The production of scale models and the iterative exploration of module mounting solutions were carried out through the use of CNC fabrication techniques including laser cutting, milling, and 3D printing. The rapid back-and-forth between design and physical prototype allowed for the quick development of a custom mounting solution that was easy to assemble and install (see Figures 11 and 12).

The finished prototype ran as an installation for one month. At various times it operated in solar-tracking mode or a “light phobia” behavior. We adapted the basic setup for a Braitenberg vehicle by replacing the two motors with a servo motor. The rotational direction of the servo is defined by comparing the readings from two light sensors. Once a single Braitenberg servo was operating, a second servo with the same setup was stacked on top of the first in a pan-tilt arrangement (see Figure 5b). We implemented a reinforcement learning control algorithm to teach the module that its goal is to follow the movement of the sun (Rossi, Nagy, and Schlueter 2012). This setup gives the component the ability to track solar movements without preprogramming solar tracking paths based on geographic location. The behavior of the module makes its installation location independent of programming, and also means that its behavior responds to local instances of overshadowing. This localization of behavior is essential in adapting to site-specific and time-specific events.
During the second workshop we engaged a different group of students in the use of parametric modeling to more quickly develop adaptive facade concepts. Through the use of Rhino/Grasshopper, students developed parametrically controlled components. These components were conceptually developed into facade systems with the ability to adapt to internal and external influences. The images in Figure 15 show interior and exterior representations of an adaptive facade system developed during the workshop. The system can be fully closed for optimal solar harvesting, or opened to varying degrees in response to occupant desires.

In spite of the short timespan of these workshops, students were able to become sufficiently fluent in unfamiliar modeling and physical prototyping platforms to apply them to developing adaptive distributed architectural systems. We believe that introducing these concepts and techniques early in architectural education is key to training architects in the design of adaptive distributed architectural systems.

3.2 Teaching Adaptive Distributed Design

In addition to developing the ASE prototype, we have led two weeklong workshops on the topic of adaptive solar facade design. The workshops were conceived to determine the ability of architecture students to adopt the concepts and techniques involved in developing adaptive architectural systems. Each workshop took a slightly different approach to engaging undergraduate architecture students in the concepts of adaptive architectural design.

The first seminar week focused on introducing physical computing as a means to develop adaptive components. Students were introduced to the Arduino prototyping platform, and worked in groups of two to develop elements for adaptive solar facade components. The components were conceptually developed into facade systems with the ability to track changing solar angles and adapt to occupant desires. Shown in Figure 14a is a physical prototype of a component that could spiral open to reduce solar insulation. Figure 14b shows interior views with the facade system in various states.

In the second week of the workshop, we turned to the development of a preprogrammed series of movements to demonstrate various possible configurations, shown in Figure 13 (Adaptive Systems Lab 2012).

4 SUMMARY AND CONCLUSIONS

In this paper, we investigated the design of an adaptive distributed building envelope. We showed how distribution allows for both architectural expression and negotiation of potentially conflicting goals of occupant desires and building energy performance. In two weeklong workshops we tested
the capacity of bachelor-level architecture students to grasp the concepts of adaptive design and to implement those concepts into design projects through the use of physical computing and parametric modeling platforms.

While the integration of adaptive systems into architecture holds great potential in relation to environmental performance, user satisfaction, and aesthetic possibility, it remains an area of architecture that is largely unexplored. The reason for this may be the steep learning curve of its interdisciplinary nature. However, as an increasing number of architecture students and practitioners are exposed to these concepts and techniques, they are bound to become the catalysts of which Pask wrote, and before long, adaptive architecture will be commonplace in our built environment.

ACKNOWLEDGMENTS
We would like to acknowledge our student assistants Eva Lüginbuhl and Julien Bellot for their contributions to the development of the ASE 1:1 prototype.

REFERENCES

WEIGHTED METRICS:
SYNTHESIZING ELEMENTS FOR TALL BUILDING DESIGN

ABSTRACT
An ever-changing state of design provoked by unpredictable economies and shifting cultures necessitates a new methodology of design. Data describing constructed buildings is an untapped resource of design knowledge which, when brought into fruition, can guide designers toward efficient, synergy-oriented environments.

Designers have examined attributes of previously designed projects to understand how key parameters could inform current design practices. These parameters include gross floor area, number of stories, occupancy, material type and quantities, geographic location, seismicity, climatic influences, etc. Utilizing collected data, two informative analysis tools for intelligent design are proposed. The first is the Environmental Analysis Tool™ (EA Tool). EA Tool quantifies the estimated equivalent carbon dioxide emissions of structural components. The second is Parametric City Modeling (PCM). PCM estimates the usable area of a tower by computing net floor area considering major building systems such as structure, mechanical, elevatoring, etc.

When these tools are applied to multiple buildings at a district scale, a new level of design and planning is facilitated. Synergies of embodied carbon, material, form, wind, seismicity, etc. can be incorporated into the fabric of the built environment at early design stages when decisions are most influential.

Mark Sarkisian
PE, SE, LEED AP, Director
Skidmore, Owings & Merrill LLP

David Shook
PE, LEED AP
Skidmore, Owings & Merrill LLP