Lumental:
Web-Based Tunable Lighting Control

by

Harrison King Hall
Bachelor of Science in Computer Science and Engineering
Massachusetts Institute of Technology, 2008

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Signature of Author ....
Department of Electrical Engineering and Computer Science
January 20, 2012

Certified by ....
Kent Larson
Principle Research Scientist, Department of Architecture
Thesis Supervisor

Accepted by ....
Randall Davis
Professor of Computer Science and Electrical Engineering
Chair, EECS Committee on Graduate Student, Area 2

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Harrison Hall
Bachelor of Science in Computer Science and Engineering
Massachusetts Institute of Technology, 2008
hkhall@mit.edu

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Abstract

Dynamically adjusting the light spectrum of spectrum-tunable light fixtures promises significant energy savings over binary or incremental dimming control. To enable this level of controllability, lighting must evolve from traditional physical interfaces towards autonomous systems that rely on behavior recognition. Lumental is a system design proposal and preliminary implementation of web-based lighting control of addressable, tunable lighting fixtures for general illumination control. The system is designed to scale horizontally, though it does require relative proximity in the network topology to maintain effective temporal resolution of lighting transitons. The proposed system utilizes current technologies but is modular such that future device innovations can be supported. Solutions to recurring difficulty areas in managing conflicting desires versus constraints, space-type temporal-sensitivity and portability of preferences are presented. Unlike prior work in lighting control the system does not require dedicated control hardware or extensive technical background to operate. The system can be retrofitted to most modern commercial office buildings and provides immediate improvements to controllability of the space to both the occupant and building administrator.

Thesis Supervisor: Kent Larson
Title: Principle Research Scientist

0.1 Acknowledgements

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- **Charles Brunault** for helping me move the physical fixtures twice and for gladly repairing them when I managed to break them.
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Chapter 1

Introduction

In this chapter we introduce the motivation for pursuing this project. The capitalizing on lighting energy savings opportunities is a direct result of pursuing an home automation technologies.

1.1 Different Modalities for Energy Savings in Lighting

Energy consumption for built structures in industrialized countries comprises approximately 75% of total consumption. In a typical office building, lighting costs are about one third of total energy costs. It is estimated that roughly 40% of all lighting is wasted on spaces that are either unoccupied or sufficiently lit by natural daylight without artificial light[27]. This means that up to 10% of total energy costs are essentially wasted as no one is there to benefit from the expense of lighting a space.

In the case of useful, occupied space, ambient lighting there are several characteristics that indicate the suitability of lighting to a particular task or activity. The most obvious indicator of the usability of a space is brightness. Color rendering also impacts the usability of the space for a particular activity. Color rendering, quantified by the color rendering index(CRI)[45], is a measurement of the ability of a light source to faithfully reproduce colors compared to an ideal light source such as daylight. Tasks that are sensitive to color discrimination, such as visual arts[48] and face-to-face communication, are particularly susceptible to low-CRI environments. In contrast, reading text, writing or using a computer do not suffer greatly from a low-CRI value. While using paper-based tasks the human eye becomes attuned to the dominant wavelengths present from the ambient light. When using a computer, the screen itself is a light source which has far-greater impact due to the constrained field of view of the computer user than the ambient light source[44].

Similar to dimming a light source for power savings, it is possible to shift from high-CRI lighting to a low-CRI lighting to optimize the luminous efficacy of a light source when appropriate for the current task. Using a low-CRI setting can save upwards of savings of 25%[43] of energy use per activity. Depending on the deployment environment, the predominant task that occurs in the space could lead to significant cost reductions in typical lighting operational costs. However as the occupant behavior changes it is necessary to immediately adapt the light source to a CRI-level commiserate with the activity.

1.2 The Advancement of Lighting and Home Automation

Commodity lighting fixtures generally enable two regimes of native operation: on and off. Accordingly they are routinely tethered to the light switch[31]. This technology represents nearly 100 years of continuous use and the staying power of good design. Other methodologies have since been developed for the control of lighting fixtures. Intensity dimming[18, 9, 20] allows gradient control of individual groups of fixtures binary fixtures. Automated control of lights using motion sensors as actuators[33, 50, 36] have also seen commercial applications and success. These solutions address the basic needs of the control and operation of lighting fixtures, but as fixtures enable new regimes of operation it will also be necessary for control methodologies to change.

Solid-state light-emitting diode(LED) technology promises to be the next major shift in lighting technology[25, 21]. In addition to gains in power efficiency, package size and service life they can be designed to emit a limited spectrum. By combining several LEDs of different wavelengths, typically in the red, blue, green and yellow color bands, and independently controling the duty cycle of each channel we are able to generate a large portion of entire visible color gamut. This ability to vary the control signals of a fixture to change chromaticity, intensity, or color temperature is termed tunable lighting, and we believe to be one of the largest benefits of the LED as a lighting fixture.

While the romanticized vision of the home of the future often takes care of menial chores of everyday life, current building support systems like HVAC[11] and lighting[12] produce higher, more consistent cognitive loads. Tunable lighting will only increase these loads. Instead of controlling one variable, brightness, for the entire fixture we must control at least one variable per channel of the fixture. This, at minimum, quadruples the number of controls that must be managed per fixture. If not automated it necessitates continual costly and error-prone user interaction to maximize the benefits these technologies enable.

Even with the assumption of the automation these lighting changes, illumination transitions occurring in the space must go unnoticed by the occupant otherwise it imposes a cognitive load in the determination of why the system responded as it did. While this load may decrease with trained or experienced users, until the technology and experience are fully ubiquitous in society it can be expected to be occasionally distracting should the changes in state be abrupt. Thus for any automation system to be continuously adaptive to user behavior it must also be designed for unobtrusive, almost invisible, operation.

1.3 Contributions of This Work

This works outlines and prototypes a possible solution to the tunable lighting control problem using an open source web framework, existing wireless sensors and a industry standard DMX technology. With this system we allow users to establish behaviors, preferred lighting spectra, and rule-based control methodology from a web-based automated control system. This system is engineered to tens of thousands of spaces and users while using commodity hardware and inexpensive control interfaces commercially available today. We also chart how future developments in technology and system integration could leverage such a system for further development.

Chapter 2

Context

In this chapter discusses aspects of technology, policy, and biology that influenced the design of Lumental.

2.1 DMX Standard

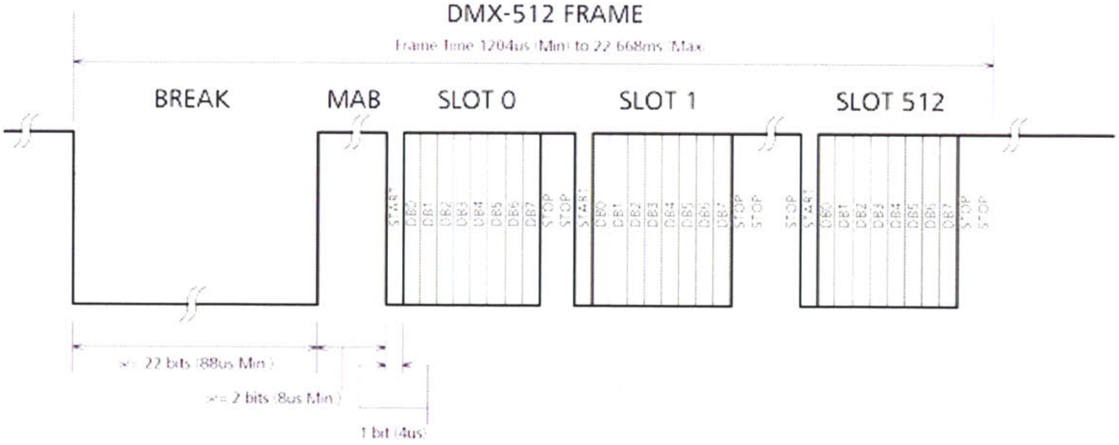


Figure 2.1: DMX is a serial, digital communication protocol used to send frames of 512 1-byte packets to addressable terminals. The devices are connected through specialized cabling in a daisy chain or ring structure and listen to addresses physically set on each device. The clock rate is $250Khz$ resulting in each bit being $4\mu s$ long and a maximum cable run length of $1200m$. A break(LOW) of at least 22 bits followed by mark after break(MAB) state(HIGH) for 2 bits indicates a new data frame. There are then 513 slots for data, the first of which is reserved for system use(traditionally null) leaving 512 for user-specified data. Each data slots is 11-bits long composed of 1 start bit(LOW), 2 stop bits(HIGH) leaving 1 byte for user data. There are no parity bits in the data. Assuming that full frames are sent, the maximum refresh rate of the DMX protocol is $\sim 44Hz$. Image courtesy of Altium.

DMX is a serial, digital protocol for passing up to 512 1 byte messages on a specialized physical hardware. The network topology is a typically a daisy chain, however rings are also supported. The link-layer medium is similar to the 5-pin XLR microphone cabling, although it has more stringent requirements on differential impedance which make using common microphone cabling error prone.

Devices connected to the network listen to a subset of the 512 channels. The network topology assumes that each device in the chain will read the data frame and place an unmodified, unbuffered version on its output port. Up to 32 devices are supported on a single run of cable, however an arbitrary number of splitter may be used if more devices are required. The address that the device listens to is physically set on the device, normally using dip switches, at connection time. This offline setup procedure allows for an arbitrary number of devices to be grouped as one logical device by listening to the same subset of addresses, however it is also limiting in that realtime modification of fixture groups is not possible through a data-only solution.

The data format for DMX can be seen in Figure 2.1. Data is asynchronously transmitted across the hardware as digital frames on a $250KHz$ clock. This results in bit being $4\mu s$ in length and the maximum length of a single cable chain being $1200m$. A data frame is initiated by a 3-byte startup message of 22-bits of digital LOW followed by 2-bits of digital HIGH. There are then up to 513 data slots, each 11 bits in length. A data slot consists of 1 LOW start bit followed by 8 bits of user information followed by 2 HIGH stop bits. There are no parity bits. A full data frame will at consist of 5667 bits and will take $22.668\mu s$ to transmit. This allows for a refresh rate of $\sim 44Hz$ with a full data frame.

2.1.1 Historical Perspective

The roots of the DMX can clearly be seen in the design of control mechanisms in Figure 2.2. Regardless of the quality and cost of the controller there are a large numbers of switches, sliders and buttons. These are intended to be used with an arbitrary theatrical lighting setups none of the controls are verbosely labelled. Both of these features indicate that they are to be used by a dedicated professional in order for them to work properly and in practice this is how they are used.

On the higher-end models pictured in Figures 2.2b and 2.2c we see the concept of *scenes* that are triggered through a button. These controls are attempts at simplification of the complex task of micromanagement of the controller for realtime playback of theatrical productions. Any stagehand, at the appointed time, can press the appropriate scene button and the lights will shift to a preset position. While this solves the problem of repeatedly hitting prescribed set points for a scene, occupants are still forced to personally interact with the device and there is still a complex setup required for a user to achieve each initial set point.

(a) Leviton MC 7000

(b) New Sunny 512

(c) Leprecon LP-X48

Figure 2.2: Three examples of physical DMX control consoles from the theatrical lighting community. They are arranged in ascending order of complexity though the modalities of interaction is largely the same: the button, the slider, the switch, and the knob. These controllers are incredibly generic in their controls but this becomes a barrier to entry for the average user.

(a) Entec OpenDMX

(b) Entec DMXIS

(c) DasLight DVC3 Gold ZM

Figure 2.3: Three examples of USB to DMX control interfaces. They convert serial USB data to the DMX512 protocol. They are programmatically controllable using off the shelf software or using a USB Serial protocol.

With the rise of cheap computation there has been movement away from physical interfaces to software solutions to DMX control. These require a DMX hardware interface similar to those pictured in Figure 2.3. These typically connect through USB although there are products that use other standards such as ethernet, MIDI or RS-232 serial. These provide a cost effective method of interfacing with a single DMX universe allowing the complexity to be shifted to commodity, general purpose computers.

2.2 Control

Control Class	Methodology	Description
Manual	Direct	Using low level control signals similar to physical interfaces.
	Preset Scene	Using single-button triggering for setting multiple fixtures to previously established set points.
Time-Dependent	Wall-Clock	Program of light transitions dependent on wall-clock time. Typically this will correspond with sunrise and sunset or typical hours of occupation.
	Internal Clock	Program of light transitions dependent on a user-defined time-based sequence of transitions. This is similar to the kind of control mechanism seen in software like VenueMagic in Figure 2.4c.
Dynamic	Occupancy-Driven	Changes according to activations by motion sensors. There is normally a direct mapping of a motion sensor activation to a present. The motion sensor is similar to a binary light switch.
	Activity Driven	Changes according to occupant behavior recognized. Is finer-grained than pure occupancy-driven in that activities are recognized and change to lighting appropriate for the task.
	System-Driven	Changes are driven by arbitrary input. This is similar to Activity Driven, though it may be driven by outside systems such as trending social media or a voting architecture.

Table 2.1: Tunable lighting control methodology classification based on the primary method of user control and system organization.

Though the initial approaches to computerized control follow directly from a need for direct, expert-level actuation, the possibilities of including a general purpose computer enables far more interesting possibilities. Table 2.1 categorizes the possible systems into broad classifications of lighting control. They are separated into classes according to the mechanism behind their control.

2.2.1 Manual Control

The manual class falls directly out of the low-level control mechanism. There are several off-the-shelf software packages for this, some of which are pictured in Figure 2.4. These software packages attempt to replicate many of the control paradigms of the physical controllers. They primarily use digital versions of sliders and

(a) Entec DMXIS (b) Q Lighting Controller

(c) VenueMagic SC+

Figure 2.4: Common software control packages for controlling lighting fixtures using software. These span the range from direct computer analogs of physical controllers as in 2.4a to time-centric control scheme representation like in 2.4c. While these packages provide set-and-forget functionality they do not yield themselves to real-time control and adaptive operation. Instead they are focused on user-triggered control and operation

buttons but can provide additional feedback about what each fixture is controlling and system state similar to what is possible in the high-end physical consoles as in Figure 2.3c.

Just because it is simple does not mean it is without merit. This methodology provides the most visceral feedback to the user. Their actions to range and control the lighting leads to immediate feedback which can drive further changes if it is unsatisfactory. This does lead the user to regularly physically interact with the system but it is an excellent failsafe control mechanism for more automated control methodologies.

2.2.2 Time-Dependent

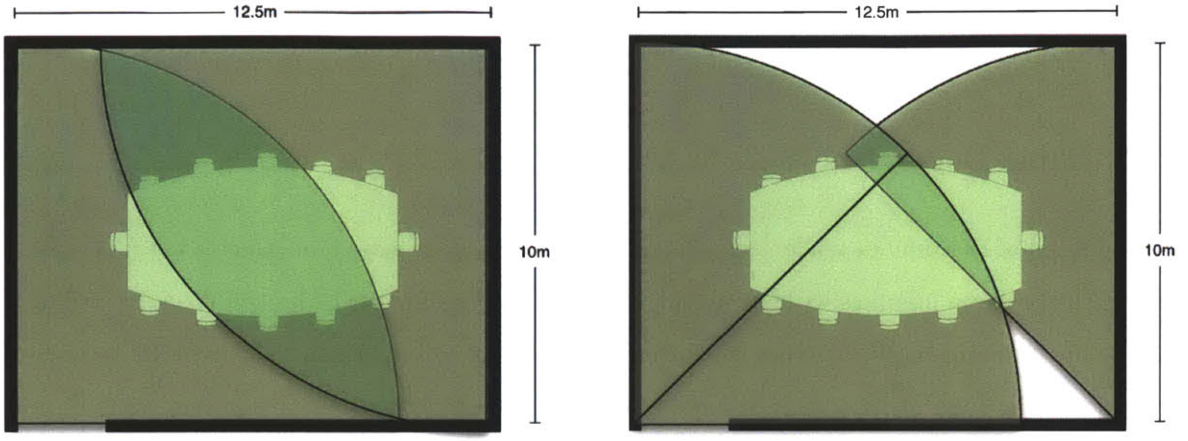
The operation of the time dependent class is reliant on a clock for actuation. Once a clock is initialized by the user the program operates without outside stimuli. This can further be broken down into categories for the type of clock referenced: whether it is external or internal to the system. The external version switches according to the time of day. This is most often realized in lighting that is triggered at dusk and dawn for on-off operation. The internally-clocked version is similar to what you might see at a choreographed light show. While this behavior is useful for entertainment or artistic installation uses, there are not many practical use cases in general purpose illumination.

2.2.3 Dynamic

Dynamic lighting is the most interesting class of control system from a design perspective. It can incorporate features of both the manual and time-dependent classes as states that are driven by external activation. The central feature of this class of lighting control is the ability to be adaptable to outside stimuli, most typically stimuli from the space that the light fixtures are installed in, however other possibilities exist.

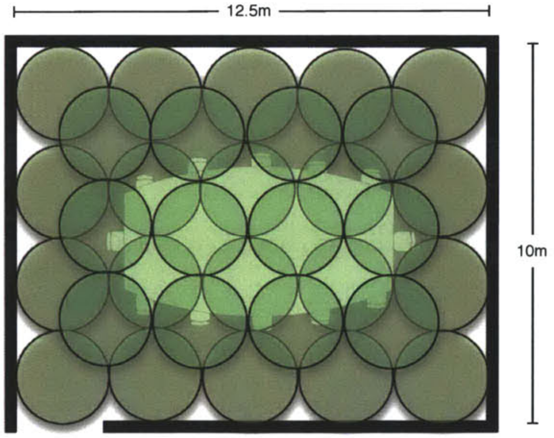
2.2.3.1 Occupancy Driven

Occupancy-driven lighting changes are already widely employed, although they are not typically controllable via software. The most common way or gathering occupancy data is through the outfitting of a space with motion sensors, typically measuring the changes in infrared reflections, that are tied directly to a binary power source for a fixture or set of fixtures. The normal granularity of these sensors is fairly course, typically giving a conic section of activation with a sweep angle between 90° and 135° and responsive range of roughly 10 meters.



(a) Gross Granularity, 2 sensors(100% coverage)

(b) Fine Granularity from walls(91.3529% coverage)



(c) Fine Granularity from ceiling(91.4159% coverage)

Figure 2.5: Motion sensors can be outfitted with shields that limit their visible areas. Above are three arrangements for the efficient placement of a minimal number of infrared motion sensors that maintain at least 90% floorspace coverage. Each motion sensor has a read range of 10m and sweeps out either 90°(gross granularity) or 45°(fine granularity) of a cone. They are placed in an typical, large conference room of dimensions 10m by 15m by 2.5m. The placement of sensors has a far greater impact on the number of sensors than their visible angle, but it also dramatically changes the specificity of area occupied.

While sensors with finer-granularity exist it they are not typically employed in practice. This grounds out in several practical considerations:

- There is an inverse relationship between granularity of occupancy and number of sensors required to cover a space.
- Power management and system administration become onerous as the number of sensors increases.
- There is limited information that can be inferred by knowing someone is active in one portion of a space
- Current lighting technology does not allow for capitalizing on information of small-space occupancy.

2.2.3.2 Activity Driven

Although detecting occupancy is often considered the first step in activity recognition, the accurate characterization of behavior . General activity recognition has a long history in the computer science and artificial intelligence communities but is still far from a solved problem. Activity recognition enables delivery on the promise of tunable lighting. Through the recognition of a set of activities within a space we are able to transition to a lighting spectra suitable for the activity while also optimizing for another criteria such as energy savings, occupant preference or communication.

This also allows us to subdivide the space below the division of a room. Multiple activities can occur simultaneously, each with its own local lighting setting if fixture locations allow. Conversely if there are not adequate numbers of fixtures you are able to optimize across both states such that both activities receive adequate lighting while also conserve energy.

2.2.3.3 System-Driven

By abstracting the underlying control mechanism to a system external to lighting control all together. While there is still an underlying mapping from environment state to lighting conditions, this mapping is flexible and can include several disparate sources. Examples could include a semantic mapping of words to lighting conditions where the keywords are driven from a social media stream or a an activity driven system where the current time also impacts the lighting level.

While input flexibility does imbue tremendous power, it also creates difficulties for mechanisms to govern system behavior. Probabilistic, rule-based and fuzzy logic decision mechanisms all form possible inputs to the system, However, for the purposes of separating concerns, they can be abstracted from the light management system into a single control system that directs the light manager through a single control mechanism.

2.3 Human Vision

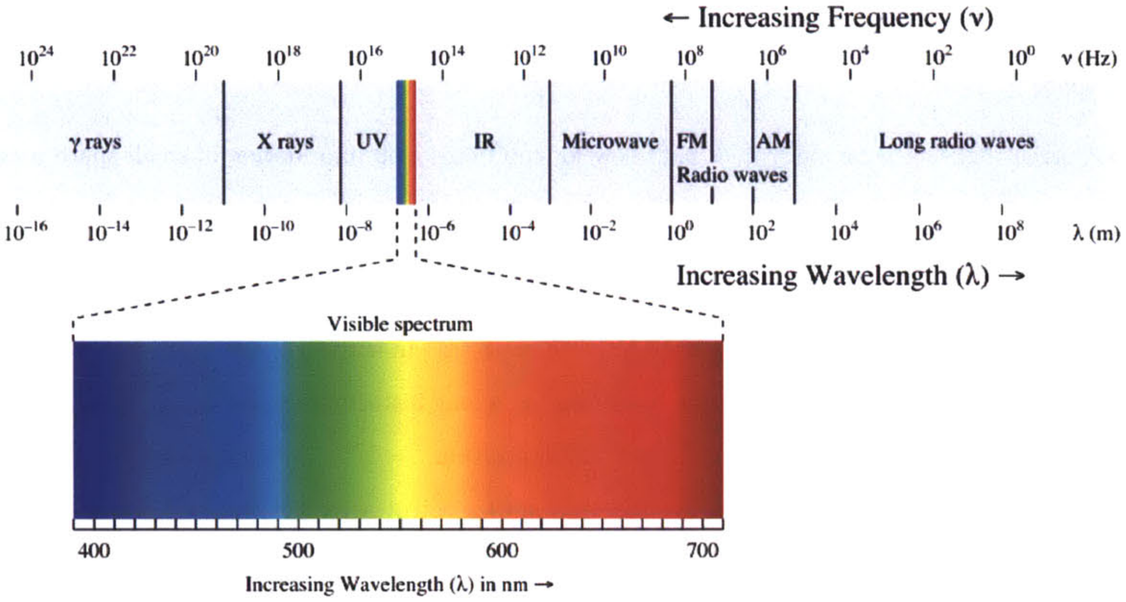
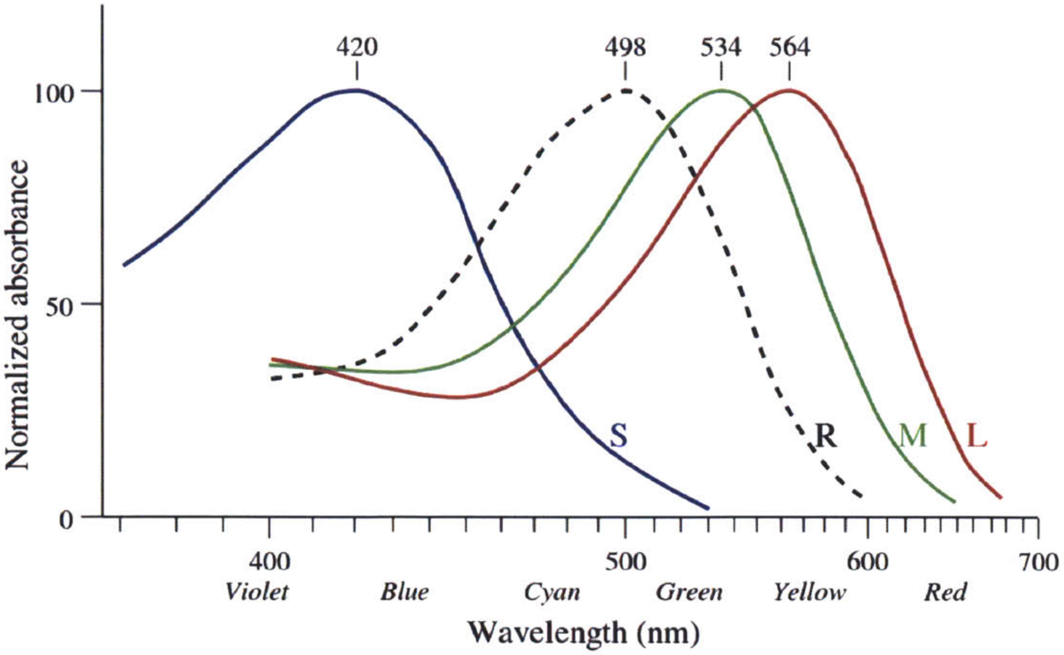


Figure 2.6: The visible light spectrum and its location relative to the rest of the electromagnetic spectrum. Zedh, "EM spectrum" August 5, 2007 via Wikipedia, Creative Commons.

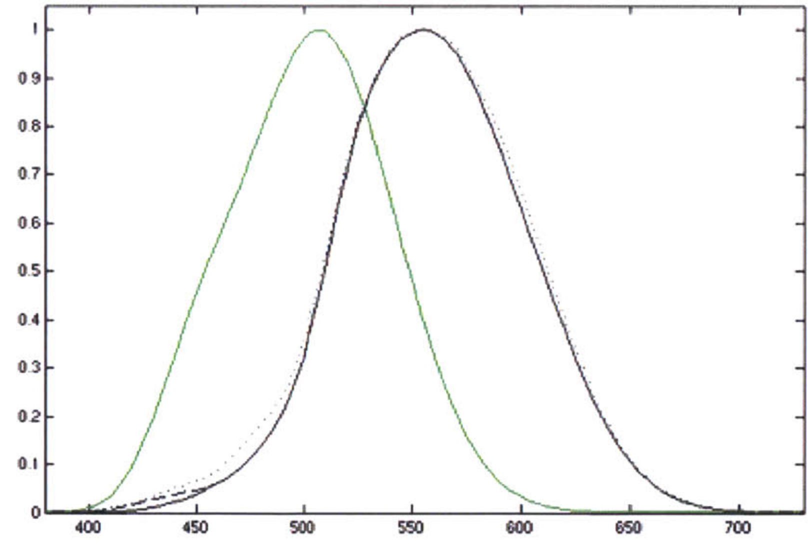
Visible light is an emission of the electromagnetic radiation that is perceptible by the human eye. A standard human observer is able to perceive wavelengths between $390nm$ and $740nm$ as shown in Figure 2.6. This frequency band is perceivable due to phototransduction of light into neurotransmitter signals in the rod and cone cells of the retina.

Rods and cones have similar structure but exhibit separate, overlapping spectrum response functions that is dependent largely on the pigment coating their epithelium. Rods respond to wavelength spectrum $498 - 640nm$. Cones come in three varieties: short(**S**), medium(**M**), and long(**L**) that are responsive to the wavelength spectrums of $420 - 440nm$, $534 - 545nm$, and $564 - 580nm$ respectively. The responsivity spectrum of these 4 types of photoreceptors can be seen in Figure 2.7a.

It is the tristimulus nature of cone cells that enable color vision. The probability that any particular cone cell is activated is dependent on both the wavelength and the intensity of the incident light. The trichromatic theory states by comparison of responses for the **S**, **M**, and **L** cones, colors can be reliably discriminated[22].



(a) Rod and cone responsivity spectrums



(b) Luminosity function of human eye

Figure 2.7: The response functions to particular wavelengths by rod and cone cells and how this translates to luminous intensity. The rods are represented by the dashed black line. Cones are composed of three types of cells referred to as S, M, and L that are responsive to a specific wavelength ranges: short($420 - 440nm$), medium($534 - 545nm$), and long($564 - 580nm$) respectively. When combined this forms a luminosity function seen in 2.7b that map an input wavelength to the normalized sensitivity of the human eye. There are two luminosity functions correlating to different luminance levels. The green plot shows the CIE 1951 scotopic luminosity function[10] in luminance of $10^2 - 10^6 \frac{cd}{m^2}$. The black plot shows the three approximations of the luminosity function under normal luminance levels: CIE 1931 standard(solid)[38], Judd-Vos 1978(dashed)[47], and the Sharpe, Stockman, Jagla & Jgle 2005(dotted)[37].
2.7a:Takasugi Shinji, "Cone response" October 19, 2011 via Wikipedia, Creative Commons.
2.7b: Ashishbhatnagar72, "Luminosity" 28 May, 2008 via Wikipedia, Creative Commons.

In practice neuron structure of Figure 2.8 performs the operations of the color opponent theory to compare the red versus green, blue versus yellow, and luminance channels as it is more efficient to transmit the different in the channels than actual channel values[24].

The wavelength-dependent response function representation of cone and rod cells does not provide a system-level view of wavelength sensitivity. Summing and normalizing the response functions of rod and cone cells yields a luminosity function mapping wavelength to a normalized sensitivity. Luminosity is based on human perception of intensity of a particular wavelength so it is an idealization and may vary between individuals. Several examples of these functions are pictured in Figure 2.7b.

2.3.1 Retina Neuron Structure

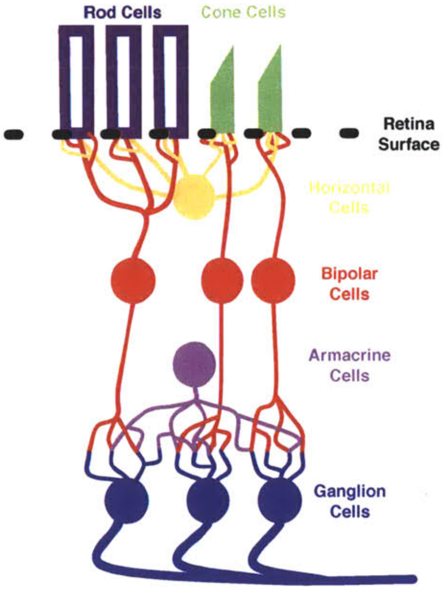


Figure 2.8: The neural retina pathway from photoreceptor through bipolar cells to ganglions. Neuron activation is indirectly influenced by horizontal and amacrine cells. Bipolar cells may synapse with a few rod cells or more than 50 resulting in a large amorphous receptor that is not visually acute. In contrast, bipolar cells only synapse with directly adjacent or individual cone cells resulting in greater visual acuity.

To signal the activation from photoreceptors to the visual cortex for high-level visual processing information compression must take place. The ratio of photoreceptors to ganglions, which connect the eye to the visual cortex, is 100 : 1. To minimize information loss the visual system uses three intermediate neuron cell types: horizontal cells, bipolar cells and amacrine cells. The arrangement of components in the retina neuron signaling pathway is illustrated in Figure 2.8. Horizontal cells synapse with photoreceptors and bipolar cells. Amacrine cells synapse with bipolar and ganglion cells. The bipolar cells serve as the direct link between the photoreceptors and the ganglions. Horizontal and amaricine cells only serve modulate the occurring synaptic activity, limiting them to indirect influence in the information transmission chain[26].

2.3.2 Retina Topology

The topological placement of rods and cones on the retina impacts spectrum sensitivity of different regions of the field of view. The average human has 92 million rods cells and 4.6 million cone cells per eye[13], Østerberg[32] characterized this layout as a distribution laterally form the fovea centralis. Figure 2.9 graphs the idealized distribution of rods and cones on the retina as it does not show the optic nerve canal. The non-uniform distribution of rod and cone cells across the retina leads to large variability in visual acuity across the field of view and field-of-view region-specific color perception and temporal responsivity.

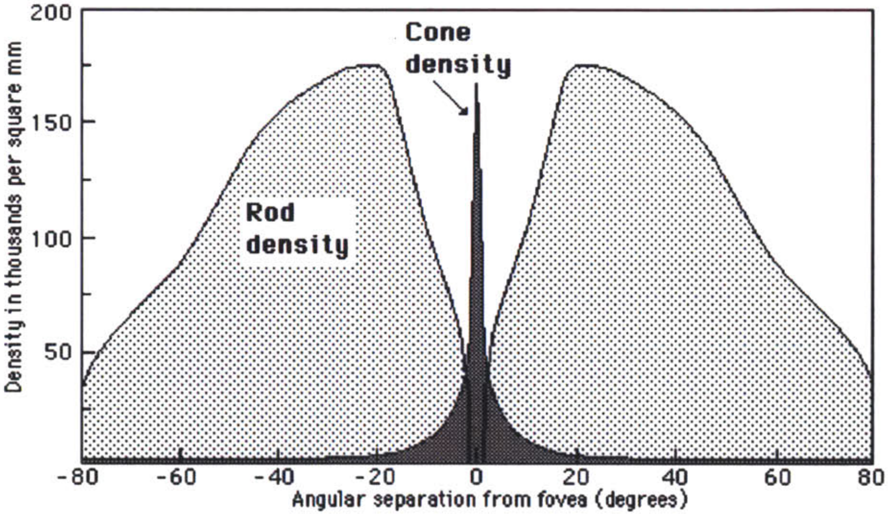


Figure 2.9: The distribution of rods and cones on the human retina. Cones are concentrated around the foveal centralis. Rods are located in the periphery of the retina with their highest densities nearer to the fovea. This structure yields fast, perceptual color in the central field of view and slower, higher light sensitivity in the visible periphery.
dadrianobiology, “distribution of rods and cones in the retina” July,2 2010 via lolatbio.wikispaces.com, Creative Commons.

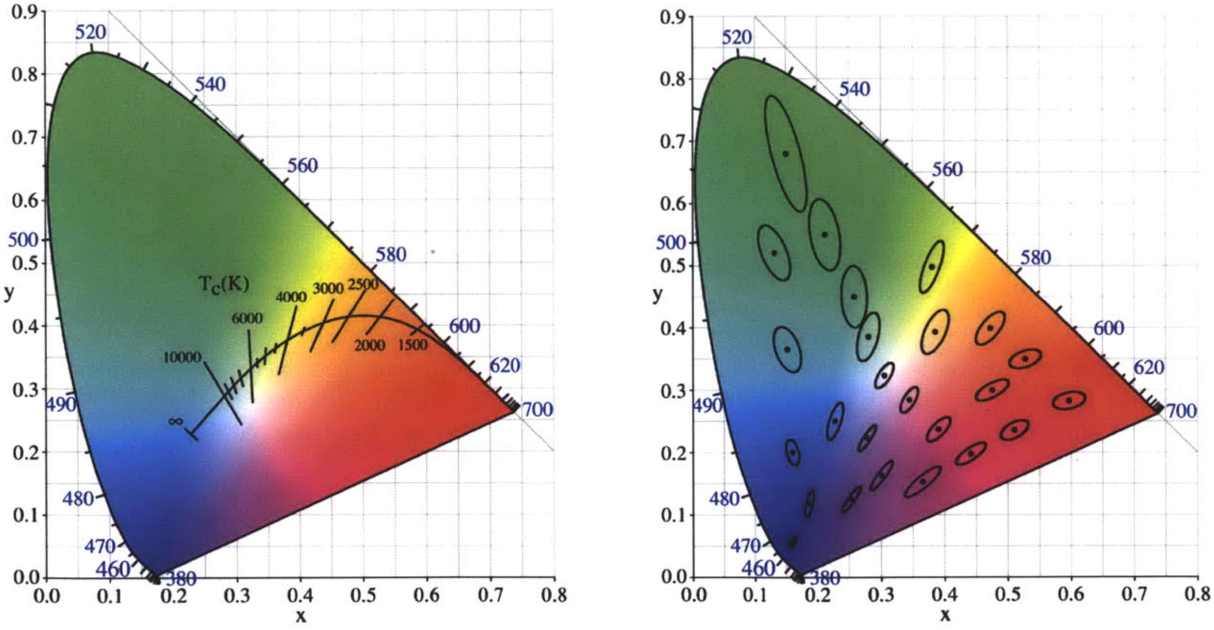
While foveal cone the density on average is $147000\frac{cones}{mm^2}$ it drops precipitously even $1mm$ away from the foveal center to a average minimum density of $\approx 5000\frac{cones}{mm^2}$ at an eccentricity of $14mm$. In contrast, rod density is $0\frac{rods}{mm^2}$ within a radius $100 - 200\mu m$ of foveal center and remains below $100000\frac{rods}{mm^2}$ until an eccentricity of $1.2mm$ before peaking at $176000\frac{rods}{mm^2}$ at an eccentricity between $3mm$ and $5mm$. After this dense ring, rod density declines in a near linear fashion to an average of $49000\frac{rods}{mm^2}$ at the periphery.

The high-density of photoreceptors both at the fovea and in the retinal periphery does not correlate to consistent visual acuity across the field of view. Within a few millimeters of eccentricity of the fovea is the only region of the retina that has accurate spatial acuity[17]. Rods and cones share similar response spectra, structure, and placement densities, but they differ on the connective synapse topological structure.

Bipolar cells form synapse bonds with either cones or rods but not both. Bipolar-cone cells synapse with between one and a small number of directly adjacent cones while bipolar-rod cells synapse with at least several to more than 50 rods. The lower convergence of cones to bipolar cells is the primary reason the visual acuity of the central field of view and that of the periphery. Similarly, the higher convergence rate of rods to bipolar cells and the $100ms$ sample integration window for rod activation, an order of magnitude longer than the integration time for cones, explains the periphery retina's excellent low-light sensitivity.

2.4 Color Space

Color spaces are models of the visible spectrum that strive to enable faithful reproduction of a specific light spectrum.



(a) Black body curve

(b) MacAdams ellipses

Figure 2.10: Rendering of the CIExy1931 chromaticity diagram with either the blackbody curve or MacAdams ellipses.
2.10a: PAR "Plankian Locus" January 3, 2012 via Wikipedia, Creative Commons.
2.10b: PAR "CIExy1931 MacAdam" June 2, 2005 via Wikipedia, Creative Commons.

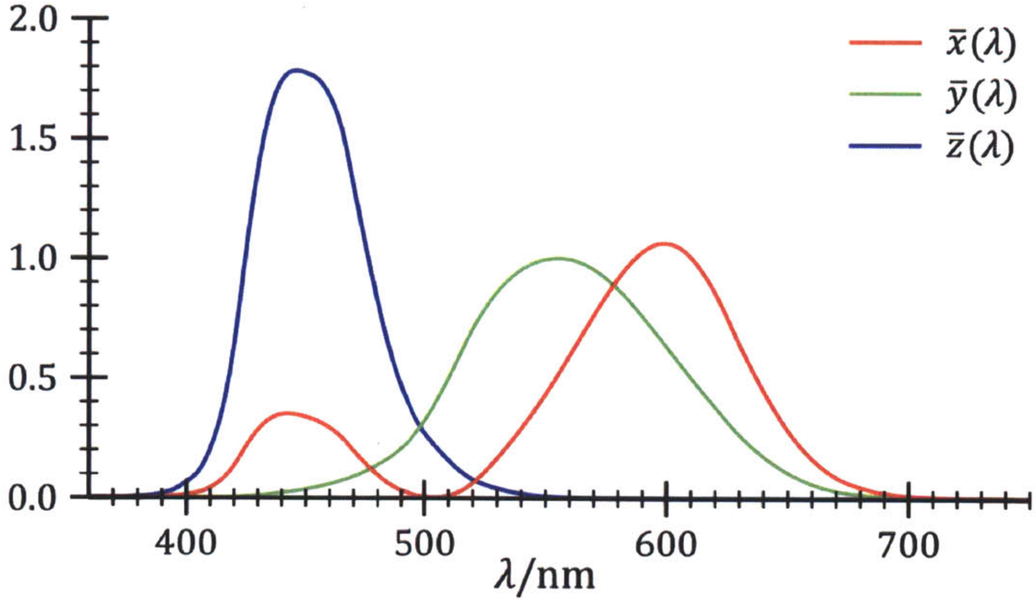


Figure 2.11: CIE1931 XYZ color-matching functions for the 2° standard observer. These represent the spectral sensitivities of human cone cells. When convolved
Acdx, "CIE 1931 XYZ Color Matching Functions" March, 15 2009 via Wikipedia, Creative Commons.

2.4.1 CIE1931

CIE1931 is a mathematically defined colorspaces based on the experimental data gathered by Wright and Guild which characterizes the spectral response functions of the rod and cone cells on the human retina[19, 49, 14]. The observed spectrum is convolved with each of the red, blue, and green color matching functions shown in Figure 2.11 render as in Equations 2.1-2.3. Then through normalization of X, Y, and Z as in Equations 2.4-2.6, we derive the x, y, and Y values necessary to define a point in the CIE 1931 colorspace.

$$X = \int_0^\infty I(\lambda)\,\overline{x}(\lambda)\,d\lambda \tag{2.1}$$

$$Y = \int_0^\infty I(\lambda)\,\overline{y}(\lambda)\,d\lambda \tag{2.2}$$

$$Z = \int_0^\infty I(\lambda)\,\overline{z}(\lambda)\,d\lambda \tag{2.3}$$

$$x = \frac{X}{X+Y+Z} \tag{2.4}$$

$$y = \frac{Y}{X+Y+Z} \tag{2.5}$$

$$z = \frac{Z}{X+Y+Z} \tag{2.6}$$

The gamut in Figure 2.10a shows a possible a chromaticity diagram of the CIExyY 1931 color space for a constant Y value. Chromaticity is the color the human eye will experience for a particular spectrum but is not directly translatable to a printable or realizable color as that perception is dependent on the spectrum of light incident to the colored surface.

2.4.2 MacAdam Ellipses

The gamut in Figure 2.10a represents an infinite precision colorspace. The human eye does not have infinite resolution of this color space, thus it can only perceive finite number of colors. This means that it could be impossible to differentiate between two points in the colorspace if they are sufficiently near one another.

MacAdams empirically determined the [28]. Figure 2.10b shows the regions surrounding 25 chromaticities that are indistinguishable from the marked point. The elliptical shape of these regions indicates that chromaticity in the CIE 1931 color space is not distortion free. This means Euclidian distance does not correspond to perceptual distance within this color space. To solve this other standardized color spaces have been developed[30, 29], but they also suffer varying degrees of distortion.

Chapter 3

Architecture

In this chapter we present our proposed Lumental architecture. Beginning with a high-level overview, we describe the requirements, our design principles and how they led to the architecture. We then define the elements that make up the architecture and conclude with a schematic figure.

3.1 Overview

The primary goal of Lumental is to enable web-based customizable lighting control framework that enables realtime tunability of the spectrum according to direct user control or outside trusted . Users should be able to utilize this framework to optimize and characterize system behavior to attempt to optimize for adversarial goals.

The Lumental architecture describes a web-based control structure that attempts to separate administration tasks from lighting behavior control in terms of time of interaction, complexity of interaction, and exception handling. The resultant network resembles a client-server architecture with real-time administration and interaction provided on the host-side.

3.2 Design Principles

The following design principles were adhered to when developing the system architecture:

- **Privacy** - This is a system that is going to have access to observe and classify potentially very personal actions. In order for Lumental to function it should not require instrumenting a space or their person with intrusive or high-fidelity sensors like video cameras, microphones or GPS-like position trackers. Additionally the system should function without having to personally identify the occupant. Similarly, if a user chooses to employ these sensors or identity-based logging then there should be no impediment.

- **Minimize User Interaction** - We want to make a system that is both easy to install and configure then becomes invisible until direct control is desired.
- **Future-Proof** - Commodity lighting technology is in its infancy and DMX is an reliable, but old and cumbersome standard. Upgrading the system components with a new standard should be as easy as writing a device controller subclass.
- **Embrace Open Source** - There are open industry standards in both hardware and software that make development and maintenance significantly easier. As this project hopes to grow into a community-supported project, we want to maximize comfort of future collaborators by providing them with a familiar toolchain.
- **Be Cheap** - There are already commercial lighting systems that provide similar functionality for generic lighting control. The downsides often include: expensive, required proprietary hardware, minimum system size is overkill, and vendor lock-in. We want to avoid all of these we build atop of widely available and inexpensive commodity hardware.
- **Control Anywhere, Anyhow** - Do not place limits on how interactions are driven by the system. Any device or system that can send industry IP messages should be able to control and interact with the system.

The only facet of our design principles we are not able to maintain is **Be Cheap** as it relates to current offerings on tunable lighting fixtures. The fixtures that we used were custom-made prototypes provided by a lighting manufacturing company to be power efficient in a particular spectrum. While the prototypes are expensive, at production volumes the cost per fixture will drop to be available to any homeowner.

3.3 Architectural Elements

In this section we describe the abstract architectural elements that comprise Lumental.

Division	Description
Space	Tree structured arrangement of actual spaces
Policies	Administrator defined regulations that all rules within a space must follow in order to be activated.
Rules	User defined "If-Then" statements that trigger lighting transitions. Their behavior may change depending on policies in the spaces they are defined.
Fixture	A physical device that is capable of outputting visible light.
User	People that use the system. They are either administrator or occupants.
Spectrum	A lighting state that is defined per-fixture as the output for each fixture can have a variance.

Table 3.1: Logical divisions to the lighting control problem.

3.3.1 Spaces

Space is fuzzy term that has a variety of scales and resolutions. Architecturally space can represent everything from a room to an entire building to the landscape surrounding a building. This variety of scopes does not limit the utility of the term in a practical sense, but it does require further specificity in order to be useful computationally. As seen in Figure 3.1 there is a general language about the resolution and level of encapsulation of physical spaces. While not all of these are realized in every architecture, it provides a framework to move toward increasing granularity: from geographic region to building to smaller and smaller divisions within the building.

These distinctions between scope become important in the outlining of policies regulating the behavior of a space. This is evident in any hierarchy-structured environment. The military is an signature example where those responsible for establishing the high-level policies are separate from those tasked with acting on those policies. The analog in lighting could be a high-level policy of keeping energy consumption below some time period allotment while each subordinate space has autonomy to interpret this policy in a variety of ways resulting in an independent selection of lighting states that support overall goal.

In practice this hierarchy of space plays out as building successive layers of building ownership and control summarized in Section 3.3.6. Let us take as an example a multi-story office building with numerous offices each with divisions, groups within those divisions and employees. At the lowest level we have an individual working in a cubicle in a shared open space. The workers might have control over the illumination of his particular desk while his group or supervisor sets policies for lighting they find pleasant for the room as a whole. The office director establishes policies for the office as a whole such as governing hours he wants people in the office or goal lighting costs. The building maintenance supervisor can set policy for the entire building or independently for each office or floor night time or security lighting.

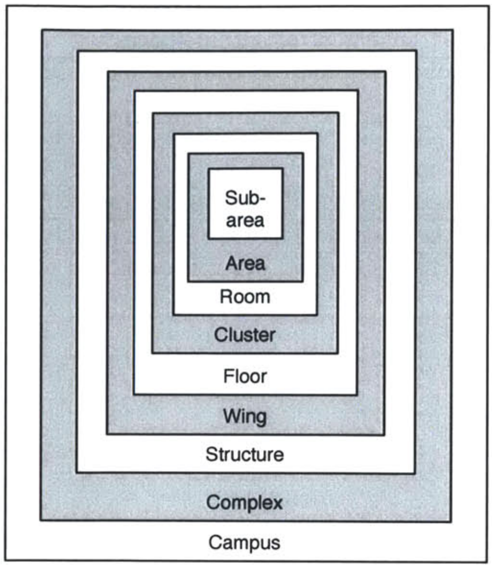


Figure 3.1: Representation of the different resolutions the term space may take. Beginning with the largest, campus is a grouping of several built structures and their surrounding space. A complex is a grouping of several buildings within a campus, generally for a unified purpose. A structure is a built structure or outdoor area separate from, though possibly connected, to other buildings and outdoor spaces. A wing is a large, connected subset of floors within a building, often with a common theme or purpose. A floor is a continuous horizontal plane within the building. Cluster is a grouping of rooms. A room is a spatial volume enclosed by walls. An area is physically local division within a room. An area can have further, smaller sub-areas that are more specific either spatially or to a particular task.

3.3.2 Tree Structure

Most representations of spaces are derived from site plans or floor plans. Floor plans easily generalize into connected graphs where the nodes represent the space to be represented and the edges represent the adjacency of or traversability between the spaces. This representation is useful if you are attempting navigation within a building or trying to understand impact of proximity spatial relationships on spaces.

The goals of lighting control do require an understanding of the relationship between spaces, light from adjacent spaces has a measurable impact even in the periphery[43], by defining a order on the granularity of the term space as in Section 3.3.1 above, we have also given ourselves power to classify spaces into a hierarchical tree structure. This is a different representation scheme than most physical-space-in-the-digital-world are presented which use a generalized graph derived from the floor plan. The nodes of the tree are still spaces of all granularities, but the edges are now directed and represent the relationship that the child node is a subordinate to the policies of the parent. This construction enables a direct, clear usage policies can be pushed down while still maximizing autonomy for subspaces to act on these policies as directed.

This structure also provides us a way of associating lights with the physical spaces in which they are placed.

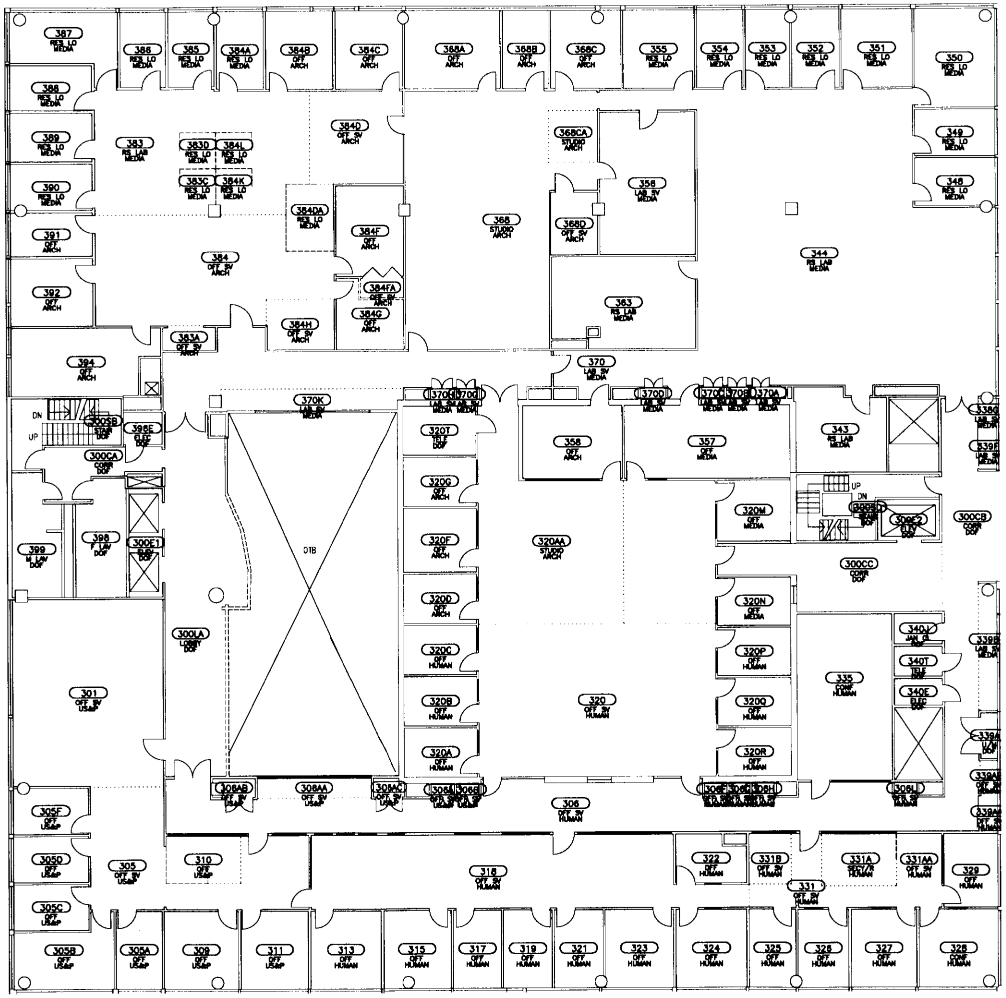


Figure 3.2: Floorplan of the Third Floor of the Media Lab at MIT.

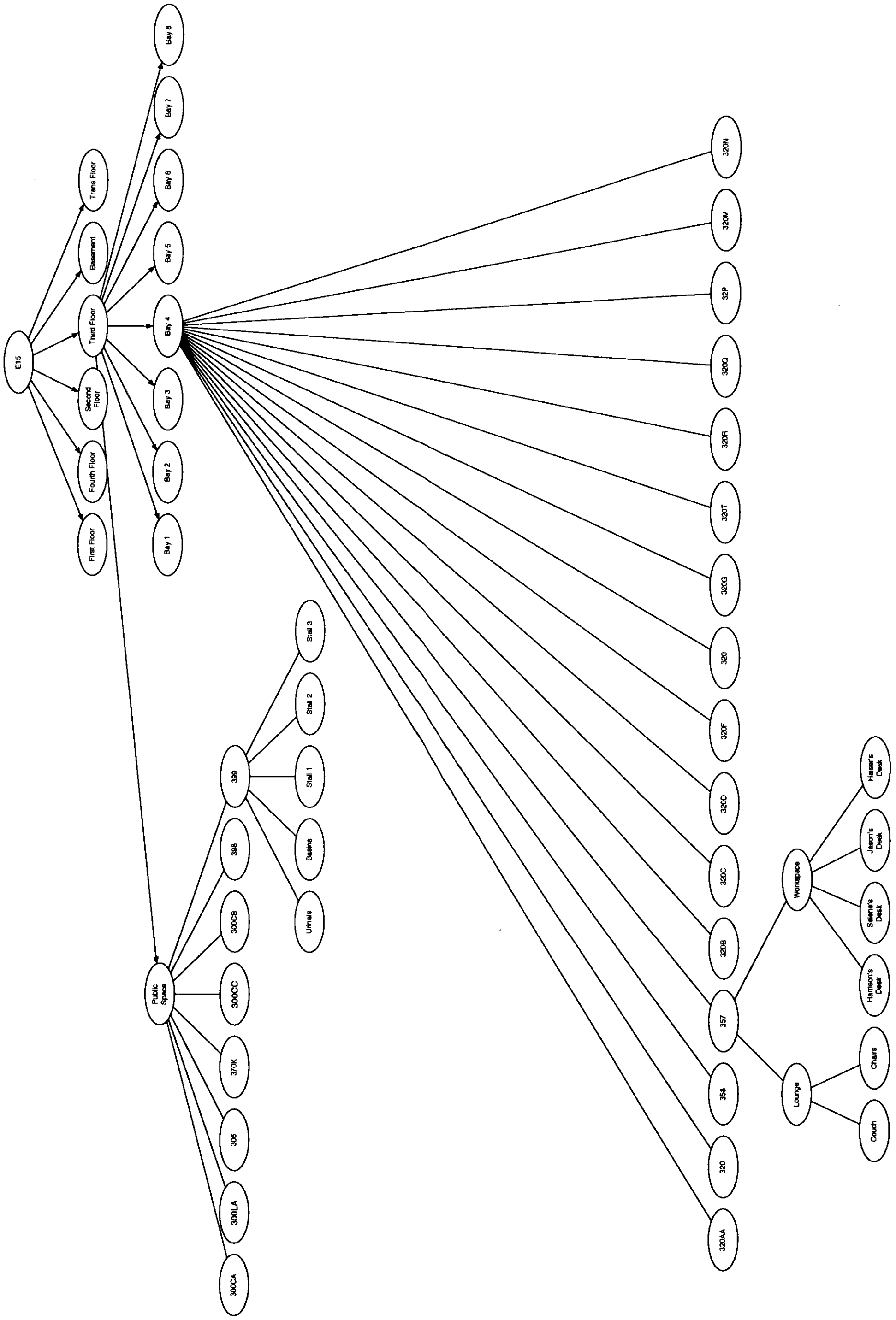


Figure 3.3: Partial tree breakdown of the subspaces of MIT's Media Lab. The nomenclature of the nodes correlates to those shown in Figure 3.2. The three shapes present represent the three general classes of space possible: circulation(diamond), occupation(oval), foyer/bimodal(hexagon). The tree extends down to the level of my office and the subspaces defined therein. Also shown are the public spaces including the bathroom and its subspaces.

Only leaves of the tree may have fixtures, as discussed in Section 3.3.3 associated with it. This ensures that policies as outlined in Section 3.3.4 still maintain practicality and applicability. The keynote example for this decision is policy definition of power management. Administrators can set goals for energy usage of the entire building. The subspaces can set their own policies to achieve these energy-use goals.

Additionally, since there is an expected hight of the tree describing the space is $log(k)$, k being the number of nodes, logical spaces, in the tree we can efficiently propagate up the tree the actions that are identified in the higher granularity sub-spaces. This allows for progressively abstract signals to move up the space tree efficiently with a known path. For realizable or practical spaces this means that these signals can appear to function in near-realtime. This enables everything from privacy-centric logging to self-driven lighting behavior based on subspaces.

3.3.2.1 Classification

Nodes in the tree-model described above in Section 3.3.2 are not identical. While it does not necessarily alter the behavior of the space it does yield special considerations given to each classification. The classifications are shown in Table 3.2 below.

Node Type	**Class**	**Description**
Non-Leaf	Meta	Nodes that are not leaves cannot have fixtures(Section 3.3.3) associated with them.
Leaf	Circulation	Spaces where there occupancy time is directly related to the dimension of the space.
	Occupancy	Spaces where the occupancy time is not directly related to the dimension of the space.
	Foyer	Spaces where there is a bimodal occupancy.

Table 3.2: Classification of spaces divided on the two primary tree node types: non-leaves and leaves. The leaves are then further divided into circulation, occupancy, and foyer spaces according to their primary usage patterns. Circulation spaces have low occupancy times by any one individual relative to their dimensionality, however the churn rate of changes in occupancy is high. Occupancy spaces have long periods of occupancy by a single person, far longer than it takes to move across them for the average occupant. Foyer spaces are bimodal in their occupancy characteristics: they have some very short occupancy times correlating to their

3.3.2.1.1 Meta

Meta spaces are non-leaf nodes in the space tree. They do not represent physical manifestations of space, but logical divisions of space. The only divergence from realizable nodes is that there is no characteristic occupancy pattern.

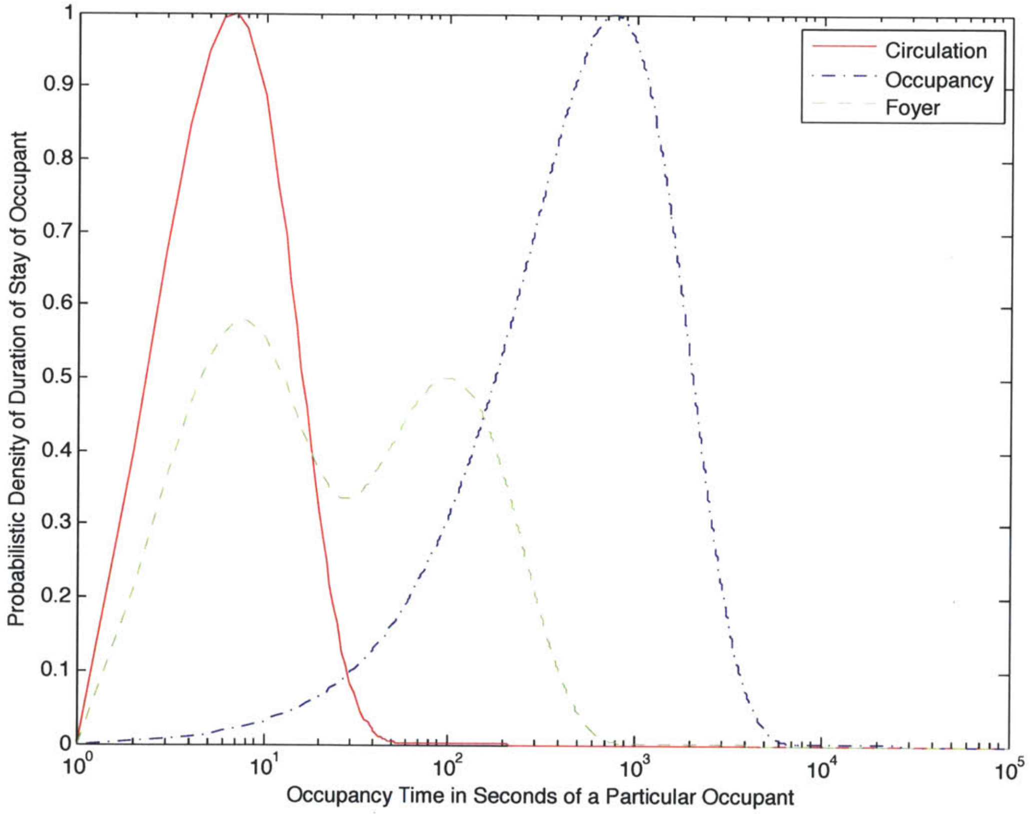


Figure 3.4: This is a graph illustrating idealized occupancy time density functions(OTDFs) for realizable space classes. The x-axis is a log-scaled and represents time spent in the space in seconds. The y-axis in the mass function of number of visits of that particular duration in units of probability density. Red, blue, and green represents the circulation, occupancy and foyer spaces respectively.

3.3.2.1.2 Circulation

Circulation space is defined by the average time it takes a occupant spends in the space relative to the dimensions of the space. This time constraint derives from the primary purpose of the space being locomotion by a participant across the space. The physical space it represents is typically, though not necessarily, organized along a long axis like a hallway. To give a reference to the timescale for this space, an hallway in an office building is $20m$ long and $2m$ across. The average walking speed of a human is $2\frac{m}{s}$. Thus the expected time a person will spend traversing the space is less than 10 seconds.

As dominant purpose of circulation spaces is to enable locomotion of occupants between other spaces we make a sweeping simplification about control of this class of space: activity recognition is not necessary, only occupancy. While a person is traversing the hallway they may be talking on a phone, conversing with another occupant, reading a sheet paper or writing a note, however the expected duration of any one entrance to the space is comparatively short. This short window for recognizing an activity and the constantly shifting location of the occupant makes it both impractical and not in keeping with the recognition strategy outlined in Section 3.2.

The timescale and churn rate for fixture state are significant factors in determining ideal lighting state. Distractions related to how quickly, how often, and how noticeable the lighting transitions should be considered when establishing the controls for this class of space. Since users are expected to be in self-powered locomotion it is reasonable to expect that their visual focus will be along their direction of travel. Thompson et. al [43] indicate that dramatic shifts in color rendering are perceptible when under direct observation, thus color transitions should be judiciously selected.

3.3.2.1.3 Occupancy

Occupancy spaces are also defined by expected about of time an occupant spends in the space relative to the space's dimension: the expected occupancy time is significantly longer than average space traversal time. The term significantly is intentionally vague as the usage patterns for every space will differ. As a general guideline, there should be at least an order of magnitude separation on the scale of seconds between traversal time and occupancy time. This separation is seen in the peaks of the red and blue graphs in Figure 3.4.

While it is theoretically possible to segment each occupant activity into a physically distinct space as was attempted by classical architecture[46], in modern practice it is not realized. Thus long-term occupancy spaces are inherently multipurpose. When optimizing lighting spectrums for opposing

The most important characteristic in occupancy-based spaces is long-term lighting quality. This quality should be variable based on the recognized behavior as discussed in Section 3.3.5. Steady-state energy use is also While lighting is diametrically opposed characteristics

3.3.2.1.4 Foyer

Foyers are entrance space that are used as transition spaces between exterior and interior spaces. This puts foyer at the interchange between circulation and occupation spaces. There are three common uses that are characterized through peak-and-trough analysis of the foyer graph in Figure 3.4.

(A) Occupants may simply locomote across the space.

(B) Occupant A meet other occupants B in the foyer briefly before transitioning to another space.

(C) Occupant A is permanently stationed in this space, possibly serving a secretarial role.

The far left peak represents case *(A)*. Transit time through the space is expected to be short and occur with frequency, though not as often as a dedicated circulation space.

The valley between the peaks represents case *(B)*. The frequency with which personal interactions occur in the foyer will determine the depth of this

The far right peak represents Case *(C)*. This is similar to the long-term occupancy timeframe of occupancy spaces, however there is an expectation that there will be a limited ruleset and a high-quality lighting spectra policy as appearing open and inviting is one of the primary purposes of a foyer.

It is important to note that this is an idealized example of a foyer space and that the usage characteristics of the physical space may result in vastly differing occupancy time density functions(OTDFs).

3.3.3 Fixtures

Fixtures are the sources of light in the space. Any source of illumination that can be modulated by electronic control signals is capable of being incorporated into Lumental. Though the primary purpose is to target fixtures that have spectrum-level control, binary switch devices can be incorporated, albeit with limited controllability.

There are three characteristics that must be assignable to any fixture to enable addition to Lumental: addressability, realizable physical location, and a realizable spectra.

3.3.3.1 Addressibility

Each fixture must have an globally unique and reachable endpoint within the scope of its Lumental installation to enable unique identification and control. This is not just a unique name, it is a means for communicating control signals to the device through a traversable signal path. We believe that IP is a protocol with a long future, but in our attempt to support current addressable lighting we provide a layer of indirection using an distributed queuing framework based on the advanced message queuing protocol(AMQP). The requirements for this indirection are detailed in Table 3.3.

Parameter	**Accepted Types**	**Description**
AMQP Address	$(< String >, < String >)$	Tuple representing the (virtual host, routing key) in the AMQP
Endpoint Address	IP Address:Port	IP address of the endpoint controller
Fixture Address Type	{IP, DMX, ...}	The type of last-mile network the fixture is attached to so the endpoint controller knows what protocol to communicate over.
Fixture Address	Varies based on fixture connection	The local address of the fixture from the endpoint controller

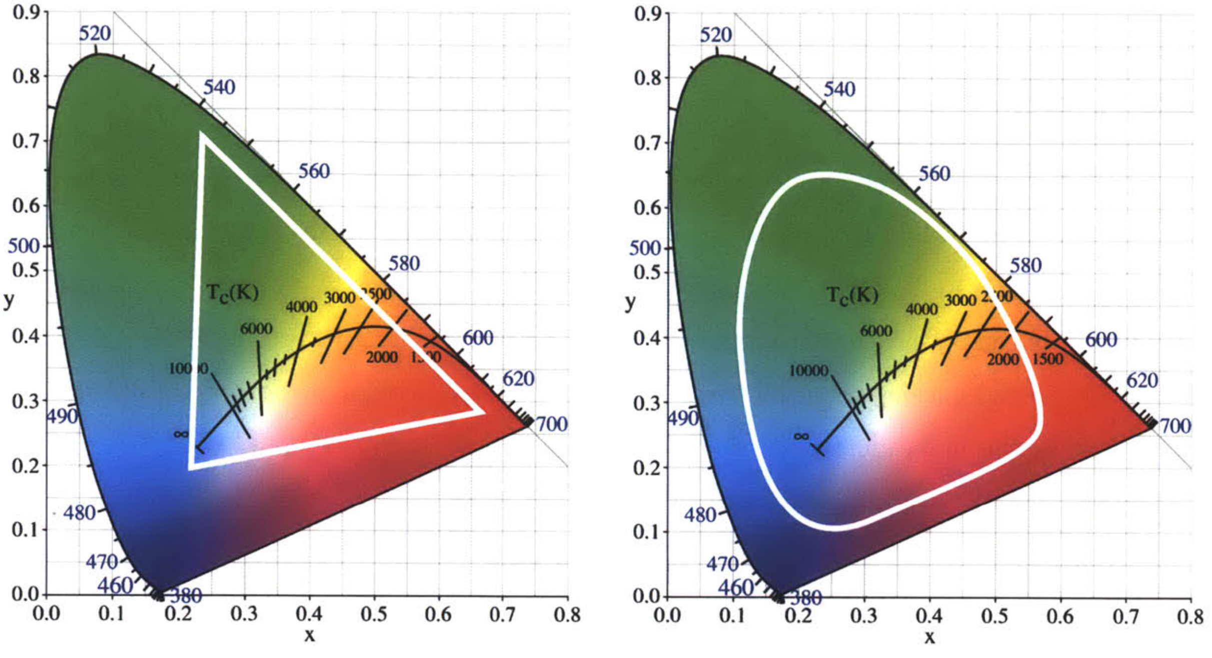
Table 3.3: Fixture address indirection parameters

3.3.3.2 Physical Location

A fixture's location must be realizable in order for it to follow the policies and respond to rules discussed in Section 3.3.4 and 3.3.5 respectively. Lumental already organizes spaces into a tree structure by administrative roles(Section 3.3.2) so we will leverage that structure to associate fixtures with a realizable space. To facilitate the this addition, every node in the space tree that is not of the meta class keeps a set of references to the fixtures that are directly within it. Fixture references do not bubble up the space tree.

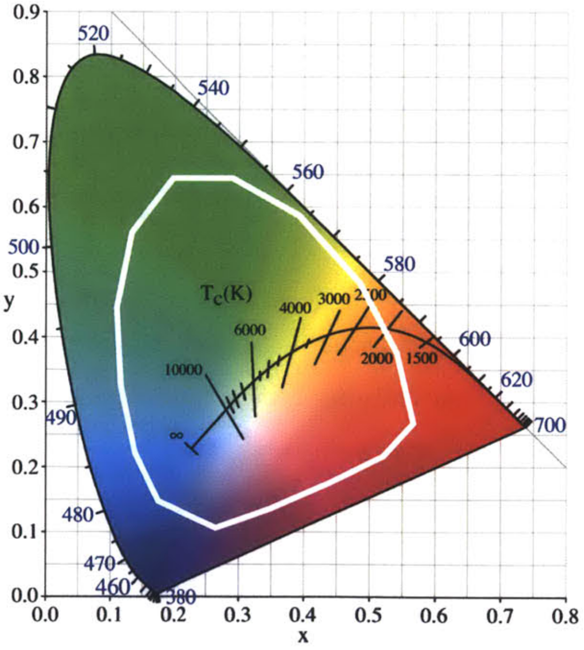
3.3.3.3 Realizable Spectra

Current fixture technology only enables a subset of the entire visible spectrum that is modeled in a full spectrum colorspace to be replicated. The topologies of several possible realizable color gamut for fixtures are depicted in Figure 3.5. We represent the colorspace realizable with this fixture as a visit-order list of points in the 1931xy chromaticity diagram. Alternatively if the color space is a set of discrete points in the



(a) Tristimulus RGB

(b) Complex Boundary



(c) Polygonization

Figure 3.5: Different subsets of the 1931 colorspace renderable on fixtures. The space inside the triangle in the standard CIE 1931 gamut are the chromaticities realizable on this fixture. This subset of the 1931 space is definable by the vertices of the shape. If the edges of the space are non-linear, an arbitrarily close polygonization is created and those points are used as in 3.5c.
Original work by PAR "Plankian Locus" January 3, 2012 via Wikipedia, Creative Commons.

chromaticity space or a input values when the chromaticity of a fixture is not known, a list of the points or inputs is also acceptable.

3.3.4 Policies

Policies are used as constraints pushed down from the parent space to all descendant spaces that must be satisfied regardless of the rule employed. They can limit the employment of rules, should no output exist for that particular rule that satisfies all the policies, but more often they specify the output of a rule from a subset of outputs. Arbitrarily complex policies can be constructed from the policy elements listed in Table 3.4 or added by the user as an extension to the system through the use of boolean operators between the policy elements.

Type	**Parameters**	**Data Type**	**Description**
Time	Time of Day	hh:mm:ss	Policy active time window
	Comparator	*Before, After*	
Date	Date	dd/mm/yyyy	Policy active date window
	Repeat	*False*, *Through*(yyyy), ∞	
Day of Week	Day of Week	{*Sun, Mon, Tue, Wed, Thu, Fri, Sat*}	Day-based active window
	Repeat	*False*, *Through*(dd/mm/yyyy), ∞	
Avg Power	Time Period	TimeDelta(*dd:hh:mm:ss*)	Maintain a power usage to match a quota
	Power Usage	w in Watts	
	Comparator	$\{<, \leq, >, \geq, =\}$	
Colorspace	Bounding Box	$\{(x_1, y_1), \ldots\}), \ldots\}$	Bounding area of the colorspace.
Temperature	Color Temperature	k in Kelvin	Goal color temperature
Light Level	Lumen Output	l in lumens	Maintain a set brightness.
	Comparator	$\{<, \leq, >, \geq, =\}$	
Transitions	Maximum Number	n, an integer	Limit the number of transitions in lighting
	Per Time Period	{*min*, *hr*, *day*, TimeDelta(*dd:hh:mm:ss*)}	

Table 3.4: A subset of all possible policy elements for constructing policies.

Policies being pushed down through the space tree does create a conflict resolution problems. Several possible challenges occur purely within the policies:

(A) Parent-descendant policies can result in contradictory requirements where there is no way to satisfy the policies of both spaces.

(B) Policies at the same node have contradictory requirements where there is no way to satisfy both.

(C) A parent-descendant pair may specify the same class of policy-element.

(D) A policy at a node is dependent is on the structure of its descendants.

These cases are solved by referencing the authority implied in the hierarchy of the space tree. At the creation and modification time of a policy, a satisfiability checker is run that ensures there are no conflicting policies within a single space or any space and a space on its ancestor tree. If there is a conflict the systems response is varies depending on the case. In the case of *(A)* the lower depth space's policies take precedence. Consequently the administrators of the descendant space are automatically notified and the subordinate policy is suspended until it can be rectified by the appropriate administrators. The case of *(B)* is solved at time of creation or modification of each policy: the system refuses to create a conflicting rule.

Challenges *(C)* and *(D)* are not an error cases, they are design consideration. Progressive administration of subspaces as considered by *(C)* ensures administrators can be proactive in setting stricter guidelines. In the case that they choose to set less strict policy requirements is the stricter policy is what dominates, else their stricter policies will be enforced. *(D)* addresses the subdivision of a policy to account for the structure and behavior of its children. Our solution is to divide according sum to the number of fixtures in the subspace.

3.3.5 Rules

Rules are used to initiate transitions to lighting scenes when certain criteria are satisfied. Rule criteria are stimulated by out of band input that we have abstracted away from the core functionality of Lumental in keeping with the design principle of future

When they successfully fire their activation to their parent space for cascading rules. They take the structure of rule-based systems complete with boolean operators. These boolean operations may be backed up with complex decision making algorithms, however the user definitions also simply if-then statements.

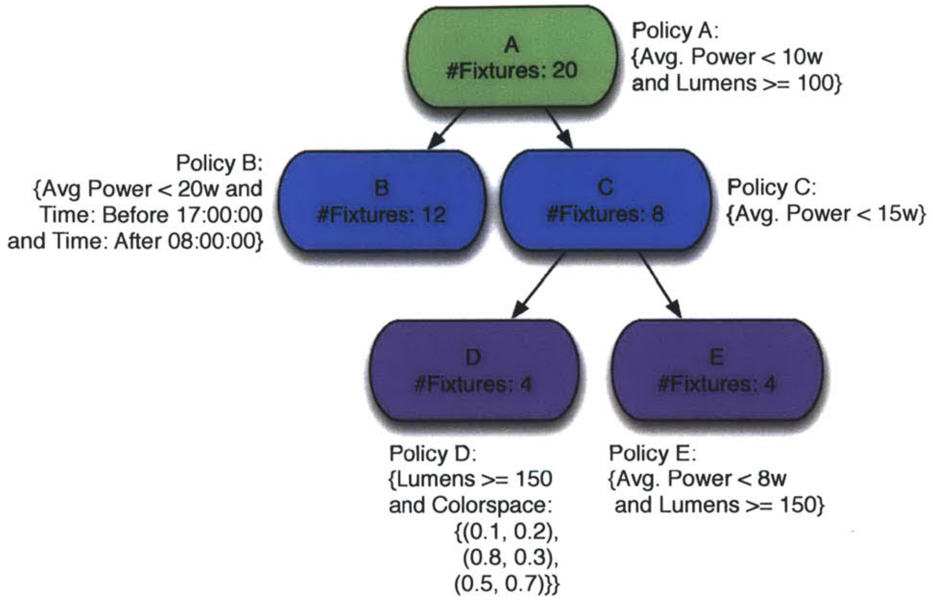
There is are complications when a rule being triggered does not result in the rule activating:

(A) Rule never fires as it violates a policy definition on the space it is on or one of its ancestor spaces.

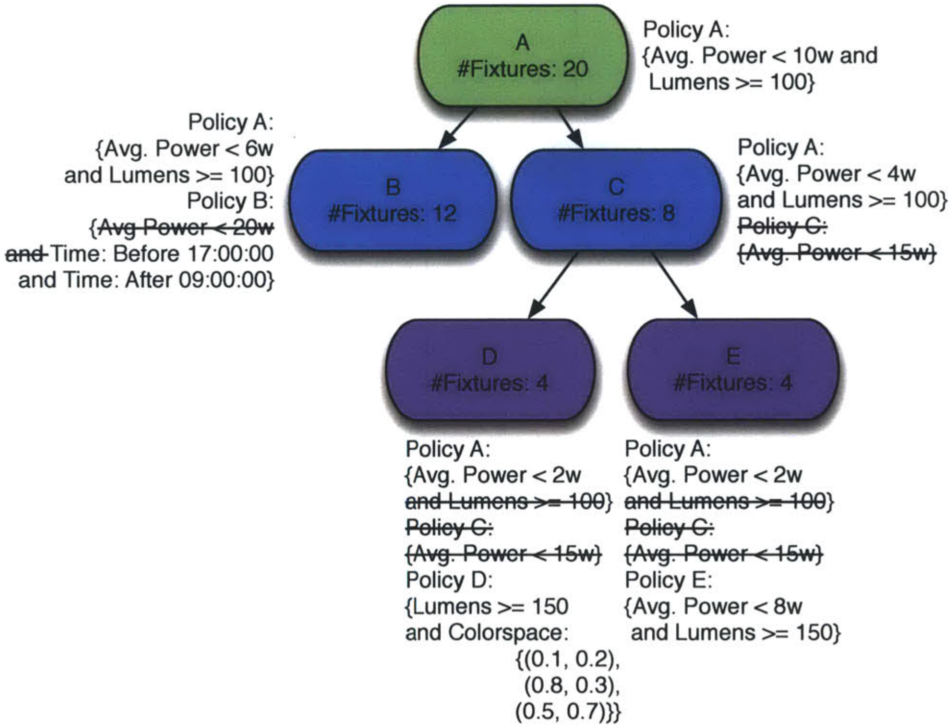
(B) Two rules trigger simultaneously or in close proximity to one another.

When a rule does not fire because a spectrum could not be found as in *(A)*it is logged and the fixture alerts the space that there are rules which violate enforceable policies.

We solve the the temporal sensitivity of rules as described in *(B)* by referencing the **Control Anywhere, Anyhow**. We take the this to the extreme that Lumental is purely an enabler for sensing packages to physically manifest their output. We also implicitly trust these external systems to be truthful and non-malicious in that their most recent input accurately represents the current state of the world. The worst

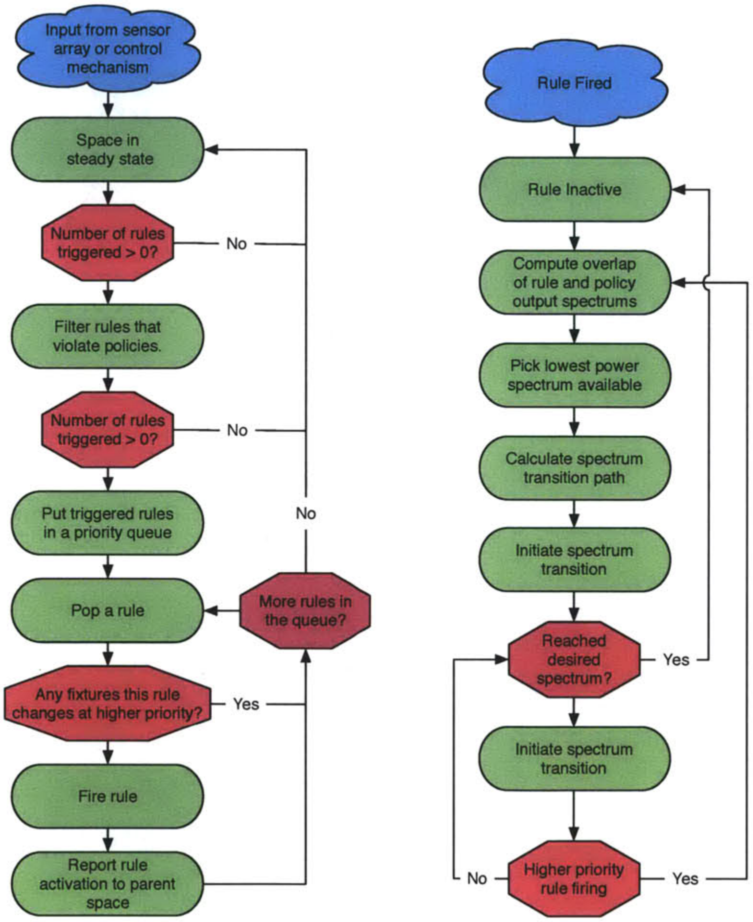


(a) Policies as defined



(b) Policies after downward propigation

Figure 3.6: Effect of downward propagation of policies on policies enforced on spaces.



(a) Rule firing (b) Rule transitioning

Figure 3.7: Flow charts diagramming the ways a space determines if a rule can fire and actions taken by each fixture to influence transitions.

case scenario that two inputs arrive at exactly the same time and trigger two oppositional rules of the same priority, we randomly select one and activate it. In the case that the activity recognition system fails we assume it is confused and either output state is correct.

3.3.5.1 Out-of-Band Input

Rules are necessarily driven by out of band input from sources external to Lumental. As stated this implicitly confers trust to these systems that they are not maliciously making reports. The phrase "trust but verify" would best describe our relationship. To prevent malicious individuals from launching a man-in-the-middle attack these reports encrypted and signed using a digital certificate, however if their system becomes compromised there is nothing we can do to detect it.

3.3.6 Users

Just as there are two classes of control mechanisms, policies and rules, there are two classes of user, administrators and stakeholders, defined on each node in the space tree. Essentially each node in the tree maintains two separate access control lists that are pushed down through descendants. This ensures the design principle of minimization of user interaction with the system as users must only be allocated access at the highest node they can safely alter all descendants.

The access control lists for administrators and stakeholders represent completely independent groups of people. Being an administrator is like a member of the board of directors of a company: they are individuals that are responsible for overseeing the long-term operation but have no impact on day-to-day operations. In contrast, stakeholders are more akin to the midlevel managers that see benefit in charge of daily operations but have no say in long-term strategy. Administrators have the ability to define space tree structure and set policies on spaces. Occupants are able to modify fixtures, establish rules, and change the currently active rules within the space.

There is also a logical third class of user but they only interact with the system in a passive way: the grazer. They utilize the lighting but have no impact as to how the lights are controlled in the automated-enabled spaces, they just use the space and enjoy the lighting.

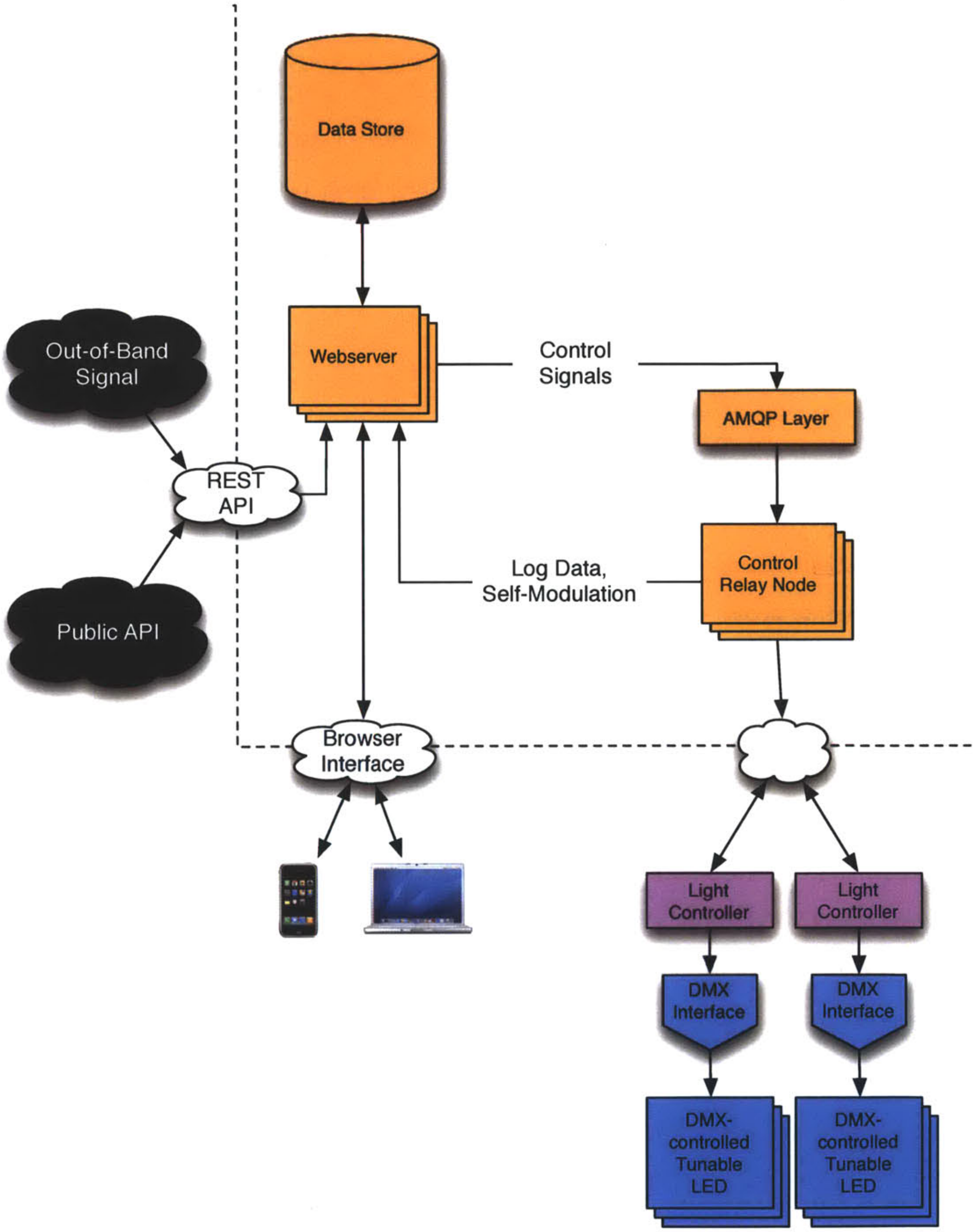


Figure 3.8: High-level architecture of Lumental

3.4 Architectural Schematic

Lumental exhibits a fairly simple component structure shown in Figure 3.8. The major divide in the diagram is between the out of band systems that interface with Lumental but are abstracted to separate concerns and future proof the system against newer activity recognition technologies. Within Lumental there are three information loops: control change, out-of-band signal and self-modulation.

The control change loop is user driven. This is when the user is modifying the currently active set of rules in a space or directly controlling the state of fixtures. There is a low temporal sensitivity on these messages so if the system is under heavy load we can delay acting on them. These arrive at the web service and depending on the URL and post data get sent to the correct routing queue. The control relay responsible for this queue then picks it up and transmits the request to change along with the program instructions to light controller installed in the physical space which interprets and alters the lighting conditions.

Out-of-band signaling comes from sensor arrays and behavior identification software that from outside of Lumental. These signals are the most temporally sensitive as Lumental attempts to always reflect the state of the space in lighting. They come in through web service and depending on the URL are dispatched to a routing queue and picked up the control relay node which processes the input for that particular space determining if it yields a change in lighting state. If it does it sends that transformation information to the light controller which translates that to control signals for the lights themselves.

Self-modulation is very similar to out-of-band signaling except that it represents state changes that are driven from within Lumental. These arise from rule firings bubbling-up spaces tree hierarchy. The signal is handled in the same fashion as out-of-band except it comes from within Lumental. As it is expected that these changes will occur more gradually than direct signaling this longer signal path is acceptable.

3.5 Architectural Subsystems

This section we discuss the function and design of the primary system components shown in Figure 3.8.

3.5.1 Web Service

The web service is the primary means of interfacing with Lumental. It is a standard HTTP-based RESTful web service running onto of a web server, like Apache. It provides a horizontally scalable front end to the system as we can replicate web server and place them behind a load balancer to ensure we have the throughput necessary. The API discussed in Section 3.7 used when talking to the web service and provides administrative and behavioral control of Lumental.

Users and out-of-band signaling services register with the web service to gain security credentials and the dynamically generated, installation specific URLs. This enables both security through obscurity in that the specific URLs are long enough that to guess them would be computationally infeasible and avoidance of man-in-the-middle attacks that could change system. Using these credentials they may begin making POST and GET requests at the various URLs to interact with the system and drive behavior.

3.5.2 Data Store

This stores all of the operational and historical data about the operation of Lumental. While it is currently specified to interface with a relational database system, moving to a NoSQL solution is possible, though probably unnecessary. This is a write-heavy system as we expect systems to cycle infrequently, generating the bulk of the reads, and steady-state behavior is to log data from the out-of-band signals and space behavior according to rule activation.

As such the majority of our logging data will be indexible based on its association with a particular space. Due to the tree structure of spaces as defined in Section 3.3.2 we are able to shard the relational database based on those keys. This means that should the system bottleneck become data-logging reads we can scale out and alleviate the problem.s

3.5.3 Distributed Message Queue

Built using the advanced message queuing protocol(AMQP) standard, the distributed message queue utilizes a publish/subscribe architectures enable efficient information delivery from the horizontally scalable web service to the individual control relay worker threads that are managing the physical installation locations of the system. In a large-scale implementation this would be a mulitply-connected set of computers such that if a link is ever cut or a box goes down the performance of the queue remain viable. This indirection to the control relays also provides fault tolerance to the workers. If a worker thread crashes the undone portions of their job-queue is still available if it is temporally relevant to act on them.

3.5.4 Control Relays

Control relays are in 1-to-Many relationships with light controllers which, in turn, interface with the physical fixtures. Though not directly connected to any light fixtures, they simulate the state of the lights attached to the light controller and calculate rule firing and spectra transitions. Should a rule fire or a spectra transition be directed, it sends a HTTPS message to the light controller. This enables the physical endpoint controller to be a simple HTTPS listener, lowering the computational requirements for the last step in the chain.

This is structured as being on the server side of the Lumental to make error recovery easy. When a threshold of signal inputs is exceeded, typically on the order of 10, a replacement instance is spawned as we expect the previous instance to have halted. This also this increases the speed at which hierarchical rules can fire as the messaging time to the web service is expected to be shorter as this is co-located with the web infrastructure.

3.5.5 Light Controller

This is HTTPS server listening for control signals from its associated control relay and represents an entire subtree of the space tree. Since the simulation of lighting is handled by the control relays the responsibility of the light controller is to act as a hardware bridge to the local address of the fixtures. Note that if the fixtures are based on the IP protocol and publicly addressable then in implementations of Lumental the light controller could be omitted.

Being a physical interface inherently limits the number of fixtures that can be controlled through a single light controller to number of fixtures controllable per interface to the number of fixtures per interface. In the case of DMX we can control 512 channels or 128 logical fixtures, assuming each fixture has RGBY channels, per universe. There can be up to 10 universes per light controller resulting in a total of 1280 logical fixtures.

3.6 Protocol

Lumental is built as a collection of RESTful HTTP-based services that provides a web-facing API for client devices and control. To ensure the validity of commands and signaling verification of the identity of the sender and confidence in the message contents is required. HTTPS[35] provides such assurances and is used for both client-server and server-server communication over TLS. This does require each physical to have a certificate on file with the machine on the other end of the communication, however this is never expected to grow past $O(n)$ where n is the total number of devices interfacing with a particular Lumental installation, due to the system communication structure.

3.7 API

In this section we present the objects constructed by Lumental and the protocols used to interact with them. Since Lumental is a REST-based protocol the interfaces are aligned with the object models and reuse the standard HTTP verbs of GET, POST, PUT, DELETE to interact with objects. We define the object model parameters and their use within the system.

3.7.1 User

A **User** models a person or system interacting with Lumental.

Name	Type	Optional	Auto	Description
guid	char(64)	False	True	Global unique identifier assigned by Lumental
First Name	string	True	False	User's First Name
Last Name	string	True	False	User's Last Name
email	string	True	False	Contact email used for alerts
password	string(hash)	False	False	Login credentials

Table 3.5: User Parameters

3.7.2 Space

Models a space hierarchy. A **Space** is necessarily hierarchically defined with the root node of a tree defined as having no parent.

Name	Type	Optional	Auto	Description
guid	char(64)	False	True	Global unique identifier assigned by Lumental
name	string	False	False	Descriptive handle for the **Space**
parent	**Space** or *Null*	False	False	The encapsulating **Space** or none if it is a root

Table 3.6: Space Parameters

3.7.3 ACL

ACL is an access control list that is associated with a space. It is used to limit a **User**'s access to the space.

Name	Type	Optional	Auto	Description
guid	char(64)	False	True	Global unique identifier assigned by Lumental
space	**Space**	False	False	Which **Space** contacted by this **ACL**
type	{admin, stakeholder}	False	False	The type of access granted to by this **ACL**
users	list of **User**	False	False	Lists of users that are members of this **ACL**

Table 3.7: Access Control List Parameters

3.7.4 Spectrum

Physical fixtures are unable to replicate the entirety of the visible color gamut. A **Spectrum** represents the portion of that space that is renderable and the methodology to get there. Providing the goal (x, y) coordinates in the respective color space, typically CIE 1931xy

Name	Type	Optional	Auto	Description
guid	char(64)	False	True	Global unique identifier assigned by Lumental
fixture	**Fixture**	False	False	**Fixture** to which this spectrum mapping relates
boundary	list of float points	False	False	**Spaces** considered part of this **Zone**
channel_function	{channel : $F(x, y, b) \rightarrow input$}	False	False	Per channel mapping function from CIE color gamut and brightness(b) $[0 \dots 100]$to fixture specific output

Table 3.8: Spectrum Parameters

3.7.5 Fixture

Representation of a physical light apparatus.

Name	Type	Optional	Auto	Description
guid	char(64)	False	True	Global unique identifier assigned by Lumental
space	**Space**	False	False	Which **Space** that contains this **fixture**
spectrum	**Spectrum**	False	False	Color gamut that is reproducible by this **Fixture**

Table 3.9: Fixture Parameters

3.7.6 LightController

A **LightController** represents the hardware light controller discussed in Section 3.5.5

Name	**Type**	**Optional**	**Auto**	**Description**
guid	char(64)	False	True	Global unique identifier assigned by Lumental
space	**Space**	False	False	**Space** that defines the subtree this **LightController** comands
address	IP address:port	false	false	The IP address and port combination for communicating with the process that controls the lights

Table 3.10: LightController Parameters

3.7.7 Zone

A zone is a set of **Fixtures** and **Spaces** that are disjoint in the set of fixtures represented. These are used to group fixtures together for **Rule** firing.

Name	**Type**	**Optional**	**Auto**	**Description**
guid	char(64)	False	True	Global unique identifier assigned by Lumental
fixtures	list of **Fixtures**	True	False	**Fixtures** considered part of this **Zone**
spaces	list of **Spaces**	False	False	**Spaces** considered part of this **Zone**

Table 3.11: Zone Parameters

3.7.8 OutputMap

Each physical fixture is not capable of reproducing the same spectrum. An **OutputMap** is a characterization of chromaticities space that is an acceptable distance from a desired color point.

Name	**Type**	**Optional**	**Auto**	**Description**
guid	char(64)	False	True	Global unique identifier assigned by Lumental
name	string	False	False	Descriptive title for this colorpoint
targets	list of (x, y, b)	False	False	A priority-ordered list of CIE 1931xy chromaticity coordinates and brightness(float [0..100]. If the point falls outside the renderable area for a fixture, the rest of the points are selected in priory order.

Table 3.12: OutputMap Parameters

3.7.9 Sensor

A sensor is an out-of-band signaler to the system that describes observed behavior and acts to force lighting changes in the space. They have a

Name	Type	Optional	Auto	Description
guid	char(64)	False	True	Global unique identifier assigned by Lumental
placement	**Space**	True	False	**Space** where the sensor is placed or None if it is non-local
measures	string	False	False	Descriptive handle for the quantity being measured or reported
sensitivity	float	True	False	Number characterizing the precision capable by this sensor
sensitivity_scale	string	True	False	The units for the *sensitivity*

Table 3.13: Sensor Parameters

3.7.10 BooleanElement

BooleanElements are **User** definable components of a **Rule** or **Policy**. They represent individual logical statements for measurable phenomenon that can be evaluated to True or False.

Name	Type	Optional	Auto	Description
guid	char(64)	False	True	Global unique identifier assigned by Lumental
trigger	**Sensor** or **Space** or **Fixture**	False	False	The **Sensor** that activates if externally triggered or **Space** or references the state of a **Fixture**
activation_level	*	True	False	Value to which we compare data from the *trigger*. It can be any data type. Examples include: string, float, integer, list of float tuples, et cetera.
comparator	$\{\&, +, !, ==, \neq, >, <, \leq, \geq, \text{within}\}$	True	False	The comparator to use for comparison against the activation_level

Table 3.14: RuleElement Parameters

3.7.11 RuleBoolean

A **RuleBoolean** is a recursively-defined component that enables the construction of boolean expressions using exclusively OR and NOT from **RuleElements**.

Name	Type	Optional	Auto	Description
guid	char(64)	False	True	Global unique identifier assigned by Lumental
element	**BooleanElement**	True	False	A single **BooleanElement** to use as a base-case. This is null if *composition* has a value
composition	list of **RuleBooleans**	True	False	The listing of all of the top-level boolean elements to combine with an OR. This is null if *element* has a value
not_composition	boolean	False	False	Whether to combine all of the members of *compositions* or the *element* under a boolean NOT.

Table 3.15: RuleBoolean Parameters

3.7.12 Rule

Rules take three forms: externally responsive, internally responsive, and combination. They are defined by boolean combinations of **RuleElements**

Name	Type	Optional	Auto	Description
guid	char(64)	False	True	Global unique identifier assigned by Lumental
name	string	False	False	Descriptive handle for the **Rule**
creator	**User**	False	False	The **User** that created this **Rule**
space	**Space**	False	False	The root **Space** on which this Policy is defined
zone	**Zone**	True	False	**Zone** this rule acts upon. It may not actually trigger a lighting change but serve as
requirements	**RuleBoolean**	False	False	The conditions that must be met for this rule to fire.
output	**OutputMap**	True	False	Output desired when this rule fires. If *zone* is null then this is also null.

Table 3.16: Rule Parameters

3.7.13 PolicyBoolean

A **PolicyBoolean** is a recursively-defined component that enables the construction of boolean expressions using exclusively OR and NOT from **PolicyElements**.

Name	**Type**	**Optional**	**Auto**	**Description**
guid	char(64)	False	True	Global unique identifier assigned by Lumental
element	**BooleanElement**	True	False	A single **BooleanElement** to use as a base-case. This is null if *composition* has a value
composition	list of **PolicyBooleans**	True	False	The listing of all of the top-level boolean elements to combine with an OR. This is null if *element* has a value
not_composition	boolean	False	False	Whether to combine all of the members of *compositions* or the *element* under a boolean NOT.

Table 3.17: PolicyBoolean Parameters

3.7.14 Policy

A **Policy** represents characteristic on a **Space** that cannot be violated despite the lighting changes. These are pushed down to all subspaces as defined in Section 3.3.4.

Name	**Type**	**Optional**	**Auto**	**Description**
guid	char(64)	False	True	Global unique identifier assigned by Lumental
name	string	False	False	Descriptive handle for the **Rule**
creator	**User**	False	False	The **User** that created this **Policy**
space	**Space**	False	False	The root **Space** on which this Policy is defined
requirements	**PolicyBoolean**	False	False	The conditions which must be met within the space.

Table 3.18: Policy Parameters

3.7.15 Log

Every action by the system is logged with reference to the element that generated it. This enables learning and self-adaptive behavior modification.

Name	**Type**	**Optional**	**Auto**	**Description**
guid	char(64)	False	True	Global unique identifier assigned by Lumental
reference	char(64)	False	False	A guid referencing the Lumental element about which a log record is being made
type	string	False	False	The type of log that is being made
content	string	False	False	The content of the record

Table 3.19: Log Parameters

Chapter 4

Evaluation

In this chapter we evaluate an implementation of the Lumental architecture. The implementation is evaluated across the dimensions of: scalable performance and projected energy savings.

4.1 Testbed Installtion

We performed tests on Lumental using three machines running the Ubuntu 11.10 server with kernel 3.0.0-12 on Intel Core2 Duo processors clocked at 2.13GHz with 2GB of DDR RAM at 667MHz and a single 120GB SATA hard drive at 7200RPM and gigabit ethernet. Machine A was assigned primarily as a webserver but also acted as the coordination server, part of the queuing framework, and as a control relay host. Machine B functioned primarily as a database server but also acted as part of the queuing framework and as a control relay host. Machine C served as the light controller for physically interfacing with the fixtures utilizing a ENTec DMXis USB to DMX interface powered by OLA This setup was selected for testing as it allows benchmarking using network traffic as opposed to single-node messaging which would skew results. Further, most homes and all offices have at least two machines that can be partially appropriated to operate the Lumental server stack and one hardware interface to the physical fixtures. All of these machines were connected across a 8-port gigabit switch

In support of Lumental the following open source services are used Apache 2.2.20[15], Django Web Framework 1.3.1[16], Java[2], Kombu 1.4.3 [39], memcached 1.14.10[3], Mod_Python 3.3.1[4], OLA 0.80 [34], Postgres 9.01[5], psycopg2 2.4.2 [6], Python 2.7.2 [7], RabbitMQ 2.7[8], and Apache Zookeeper 3.4[1]. They are installed on the three machines as shown in Table 4.1. The RabbitMQ queuing service is the only off-the-

Machine	Installed Software
A	Apache
	Django Web Framework
	Java
	Kombu
	memcached
	Mod_Python
	Psycopg2
	Python
	RabbitMQ
	Zookeeper
B	Kombu
	Postgres
	Psycopg2
	Python
	RabbitMQ
C	Kombu
	OLA
	Python

Table 4.1: Open source software installed on each machine in testbed

shelf service replicated across multiple machines. This is a simple clustering of the machines well help us quantify how network delays impact the queuing framework.

In addition to these, the appropriate Lumental services were installed for the job that particular machine was doing. The only component of this Lumental installation that is replicated is the the control relay. In the installation setup there is only one light controller and thus only one control relay is needed, but this complication is to simulate the replication in the queuing framework. To decide which machine will handle the function, on startup of the service Apache Zookeeper is referenced and the responsibility is negotiated.

4.2 Scalable performance

There are many areas that impact performance of the system. The signaling delay pipeline of Lumental is seen in Figure 4.1. Some of these are beyond the control of the system and thus we cannot reliably benchmark outside of a particular installation. It is important that we account for these delays as it will change the perceived performance of the system.

4.2.1 Metrics

There are two metrics that we consider in determining performance of the system:

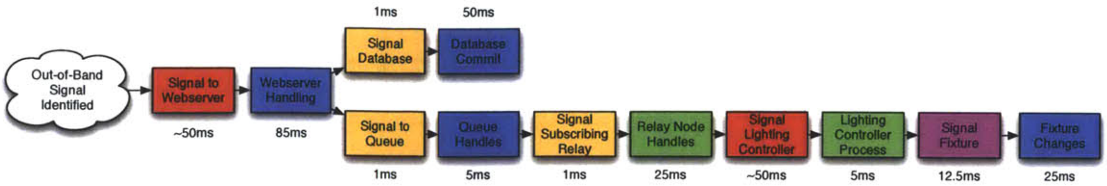


Figure 4.1: Propagation of a signal through Lumental. Starting with what we have the greatest control over, green blocks which represent the reference implementation control relays and lighting controllers of Lumental. These are able to run in realtime relative to DMX signaling meaning that if we we need to process 40 signals per second or one message every 25 milliseconds. While these are not optimized for performance(written in Python without C-bindings) they allow for quantification of how performant the system can be end-to-end. Next the yellow boxes represent the internal network hops with measured average round trip times on these to be less than$1ms$ with a standard switching hardware. Blue boxes are third-party packages that we selected to use with the system. They are running in standard configurations except where noted. The magenta box represents both a hardware and a software limitation that we experience in local address translation. In this instance we are reliant both on DMX hardware and the software package wrapping the interface, OLA. The red boxes represent the network connections that occur outside of the installation. The nature of ethernet communication and IP routing makes putting hard bounds on a transmission impossible, however we expect average round trip time to be $100ms$ if we locate the server components relatively near the client in the network topology. The times represent our average spent in each of these states during sustained load.

- **Response Time**: We have decoupled the control mechanism and signaling mechanisms from one another so that arbitrary sensor or behavior can take a significant quantity of time to reach the system. If this time is too long it will become perceptible by the occupants of the space, particular in circulation spaces, which counteracts our design principle of minimizing user interactions. We characterize this as an end-to-end performance based on an out-of-band signal and the time it takes to initiate a lighting transition.

- **Network Resources**: Lumental scales horizontally through network communication. There is significant out-of-band signaling and message passing within the server-side elements of Lumental. The average message size is 10 kilobytes very little information passes over the network, so with a very minimal server-side hardware allocation it should be possible to control a large lighting system.

4.2.2 Scaling of Traffic

To simulate a traffic load we had three machines not directly connected on the server switch sending traffic to the web server replicating the steady-state behavior where a lighting program is running continuously triggered by a signaling system with a message size replicated from what our BoxLab sensor installation reports. This signaling message is approximately one kilobyte in size and correlates to rule a resulting in a lighting transition with probability of 50%. The time is measured from appearance of the request at the ethernet port of the hardware until all lighting rules have been evaluated and not fired or lighting transition has been initiated by the light controller.

Theoretically with a 1 gigabit connection and an average message size of 10kb we should be able to handle 100000 connections. Obviously this is ignoring any server hardware limitations, but the link layer itself should be able to support this before it is flooded. The physical hardware of our machines implies that if we were to hold this number of connections in memory we could at most allocate 21kb of space to it. Less if we consider that we have to account for the operating system and other process overhead. This is a very low per-connection memory footprint so we expect to be able to saturate the system before we saturate the connection which assures us accurate benchmarks for the system.

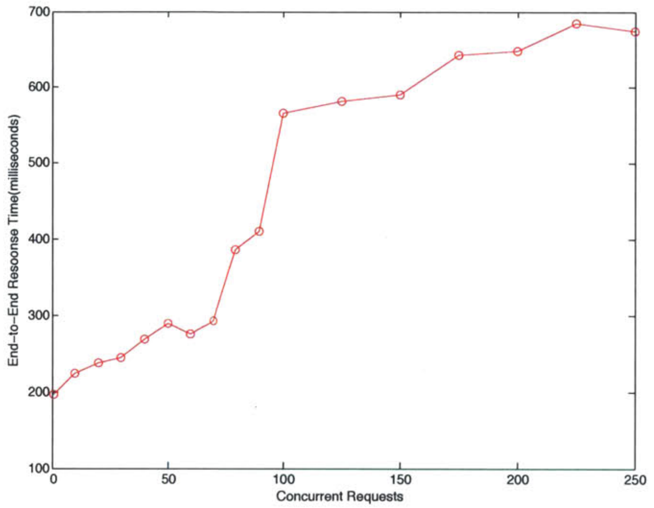


Figure 4.2: Average end-to-end response times under sustained load at different concurrencies

The response time is not the time for a signal to return to the out-of-band system, but the time to generate lighting response in the system, if the signal dictates that it is necessary. This means that we should evaluate the longest pipeline the from the out-of-band signal to the lighting change. Figure 4.1 shows a high-level breakdown of this signaling pathway and some of the measured and idealized delays in the system. The pathway we are interested in is described by the lower path. There are some aspects of the design, primarily the use of IP routing and TCP, that do not permit hard bounding on delivery time. For all communication that occurs outside of the redundantly connected server-side components we expect 100ms delays. Delays due to internal communication between machines server side was measured to be on the order of $1ms$ so we idealized that across all of the interprocess communication. The fixtures themselves are specified to operate on DMX which is requires a 40Hz response rate so both the fixtures and the system that interfaces with them must provide a signal every 25ms. We assume that these are pipelined thus there will be a one DMX period signal delay before the lights will actually change when the signal reaches the light controller. Ideally the light controller and control relay would react within this bound. The additional infrastructure of web service and queuing service are also significant as they are on the critical path and could be easily changed if their performance was the primary hindrance. Further there is an out-of-band time delay that we do not take into account as there is too much variability in system behavior. Depending on design choices the out-of-band system's time delay may dominate the delay of Lumental.

The ideal speed of the system would be less than 100ms as this would ensure that it would occur below the threshold of human visual perception. Being above this threshold does not necessitate system failure, but it make make system changes distinguishable from their causal change. This threshold primarily correlates to direct observation of some activity and not peripheral recognition, which the overhead mounted lights will be for anyone not looking at the ceiling. While the effect of the light output will be directly within the field of view, by gradually changing the lighting we can mitigate the noticeability of the change.

Lumental is above this 100ms threshold of perception as seen in Figure 4.3 for any signal that comes into the system. Even with one level of concurrency we are sitting at almost 200ms for a lighting response. Our experimental test seth also avoids the significant 50ms delay in signaling from distant-in-network-topology end nodes. This would indicate we would be closer to 300ms response time from the time an out-of-band signaler decided to send a packet to a lighting change. At around 72 concurrent reports our performance hits a wall and sees sharp slowdown in system responsiveness until performance levels off around 100 concurrent reports at approximately 600ms for the remainder of the load test.

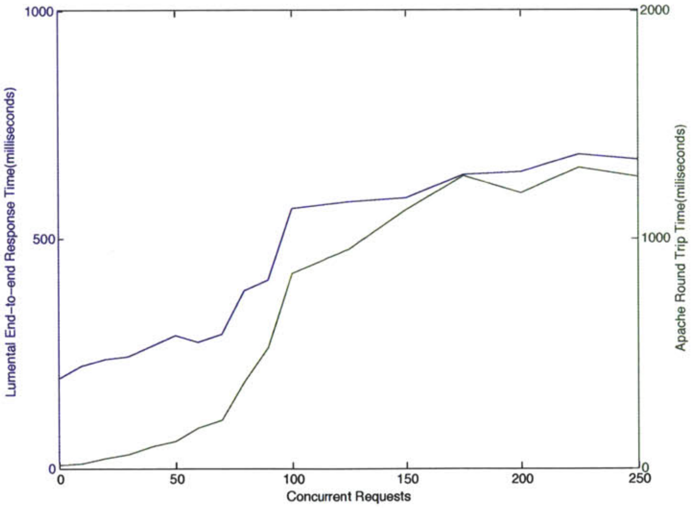


Figure 4.3: Average end-to-end response times graphed against the total response time that the Apache web server takes to process and respond to a request. At concurrency of ≈ 70 requests we see a large spike in the delay. This coincides with the similar spike in the end-to-end Lumental numbers indicating that as as signals greater concurrency is required on the web interface the delay in processing by the web server is the most significant contributor to system lag. These numbers were obtained using the Apache HTTP server benchmarking tool(ab).

Intuitively this indicates a failure in the web service as it is the part of the system that must handle the concurrency directly and cannot horizontally partition its workload. Figure 4.1 graphs the round trip service time of apache server against the time of lumental system response. The Apache responses are measured as a round trip time from the sender so network effects may be partially causing delays but we likely think it is that we prioritized signaling the queuing infrastructure over writing to the database or responding to the request as they have less impact on perceived performance. Both graphs share the same region of hyper growth around 72 concurrent reporters bounded by relatively constant growth on either side. This indicates that we have located the the main overhead in the system is in the web server.

Given the nature of the task that we are asking Apache to perform it is not all that unsurprising and we should have expected this result. Apache is a process-based service which means there is significant overhead associated with concurrency. The workload expected is inherently short sessions and optimized for high concurrency but short duration. This would lead us to an event-based server which would significantly lower the memory footprint which is where we think our problem originates. Additional tuning of Apache may also yield gains, but the most significant will still be gained when we switch handling methodologies.

With this low test result we have used less than 1% of server-side network resources

4.2.3 Start-Up Behavior

The focus of our test has been on steady-state behavior as we expect workloads to mirror our system design goal of minimizing human interaction with the system we did benchmark system initialization. There are three levels of performance for system initialization: cold, warm and hot. Our cold benchmark measures time from the state of machines powered off until the system is responsive to lighting commands. In a warm running state the machine is already powered on but no Lumental services running. Hot performance have all services running already and measure time for a program change to complete. Are benchmarks show times of 32 seconds, 8 seconds, and .74 seconds respectively. While these delays are significant relative to the scale of human perception we expect that the average rate of this occurrence will be low enough that it is an acceptable timescale.

4.3 Energy Savings

Energy consumption is based on two factors: time and wattage usage. While we have no control over occupancy time of a participant we can control the energy expended to light the space by modulating the spectra presented to them. Our fixtures did not come with a comprehensive mapping for their power per channel or how this mapped to the chromaticity space instead of full mapping which would have required 2^{8^4} measurements to be certain, thus we used the optimized set points as shown in Table 4.2 for our power reference. The numbers in this table are expectations on performance as the fixtures that we were using are prototypes with unoptimized power supplies with no way of measuring actual energy consumption.

Type	Description	Chromaticity (x, y)	DMX*ControlSignal* Values	Power Use
Tunable LED	Green	(0.321,0.572)	(0, 15, 0, 0)	2 Watts
	Blue	(0.253,0.184)	(15, 0, 64, 0)	3 Watts
	Purple	(0.244,0.185)	(10, 0, 50, 0)	4 Watts
	Warm White(Low)	(0.374,0.381)	(61, 5, 13, 61)	4.25 Watts
	Warm White(High)	(0.368,0.372)	(236, 22, 53, 255)	17 Watts
CFL	N/A	(0.427, 0.393)	1	15 Watts
Fluorescent	N/A	(0.36, 0.354)	1	60 Watts
Incandescent	N/A	(0.44, 0.401)	1	60 Watts

Table 4.2: Fixtures and Spectra used for lighting spaces and their power consumption

To evaluate energy savings with lighting we first had to evaluate how people were using the space. Building on the previous work of Tapia et al[41, 23, 40, 42] we utilized MITes sensors and the activity recognition componentry of the PlaceLab project to understand how people were using the space. There is significant power within this system to define and recognize arbitrary activities, however we chose to understand presence as a stepping stone to occupancy.

In the installation we had sensors placed in the locations shown in Figure B.2. This allowed us selective field of view but also specificity down to individual fixture which should change. By monitoring the behavior four graduate students at the Media Lab over 10 consecutive days we were able to see periods of occupancy and emptiness emerge in the data. These students kept the office occupied approximately 9.5 hours a day with multiple occupancy on average 5 of those hours. The full breakdown of time spent in the space is summarized by Figure 4.5.

As described earlier the primary benefit of automating such a system is to minimize human interaction with the system. Over the course of the entire experiment we registered an average error rate of 4.7 distinct, multiple reports within 60 seconds were treated as a single report to account for multiple occupancy states, misbehaviors . There were 1744 occupancy state changes over those 10 days yielding an average 9 minutes per occupancy state change. This is several orders of magnitude different than what we thought an occupancy space meant, although it nicely meets our definition for foyer space. This indicates that students of this office do not have sedentary work habits but are instead constantly entering or leaving the room or being interrupted. While we have no way of measuring efficiency during this time window it also indicates that

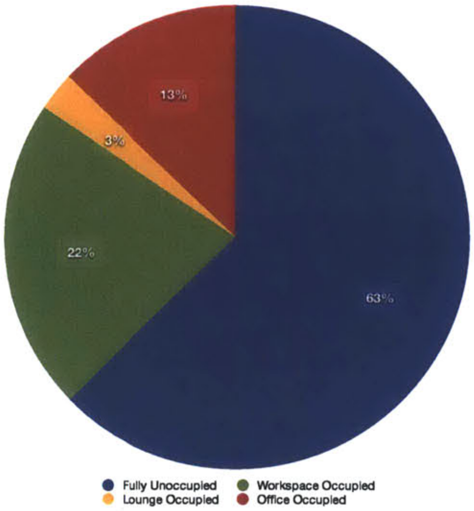


Figure 4.4: Breakdown of percentage of total time the space is used for each activity as reported by BoxLab

we should expect more spaces, particularly in shared workspace scenarios, to exhibit this kind of behavior and readjust our projections for time limits.This space may also just be an outlier in the set of all possible spaces.

Using this occupancy record and lighting rules for the space we generated the power consumption of various incandescent, fluorescent and solid state fixtures as seen in Figure 4.5. Incandescent and fluorescent fixtures are not addressable so the power output is always the same regardless of state since in a space of this size normally individual control is not provided. Clearly there is a technology win in using solid state fixtures, but more importantly we see that power consumption of individually addressable fixtures drops when behavior-specific lighting is included. In our 10 day study we saw a a reduction of 67% of the total power consumption versus constant on, 2.497 kWhr versus 6.671 kWhr, and a 15% savings versus basic occupancy, 2.497 kWhr versus 2.985kWhr, within LED alone. The difference in the latter metric is due to selecting a lower power, but illuminating, light output when a specific space is unused or used for a particular activity.

Power considerations surrounding the computer hardware required to power Lumental are marginal to total system savings. Additionally, the low computational overhead benchmarked in Section 4.2 enables this to run on computers already in the space without inhibiting normal system operations. Their presence and power load are already steady state so they were not considered.

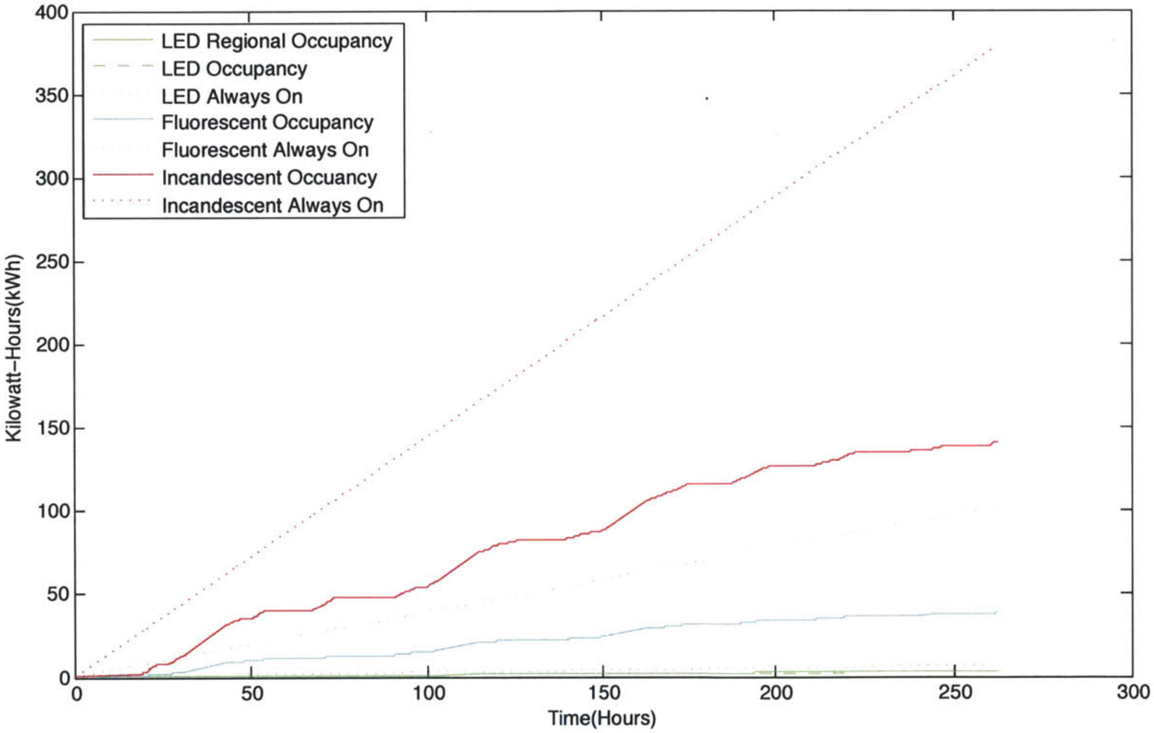


Figure 4.5: Comparison of energy consumption totals in office occupancy environment. Data collected is based on the occupancy patterns of the office installation over 10 days.

Chapter 5

Conclusions

In this chapter we give an overview of the work presented and suggest next steps for this work to be taken forward.

5.1 Overview

In this thesis we described a how tunable lighting enables a personalization of a space to an individual user's preferences to optimize comfort while also enabling activity specific lighting spectra. We described the considerations that must be accounted for when designing such a system. We then formulated a proposal to address these concerns that addresses the administration, scalability, interoperability and real-time control of such systems. We then constructed the Lumental system capable built atop of these principles. Finally we benchmarked the system to show that it can be constructed inexpensively and is horizontally scalable on commodity hardware. We also showed that significant efficiency gains of at least 15% over the light switch or primitive occupancy sensing can be attained with basic configuration of such a system.

5.2 Future Work

We expect that spectrum tunable lighting will be the industry standard in general purpose lighting with a time horizon of about 15 years. In the interim until its wide acceptance we expect spaces to become increasingly embedded with sensors and monitoring devices of both occupant and environment behavior. Currently energy use monitoring and basic control of building technology systems, specifically HVAC, are becoming increasingly popular. As this trend continues to spread, we expect the demand for computation-capable versions of todays environment furnishings to rise in turn. This will require systems like Lumental to be flexible in input as well as have more tangible concepts for control and lighting than what has currently been developed. Specific avenues we believe need to be investigated immediately for more

5.2.1 More Feedback Loops

Currently the space policies are largely useless as we do not have reporting mechanisms, either hardware or software, that is inexpensive enough to allow for pervasive installation into the space. The two examples that were sorely missed in this project are photometers and individual breaker or socket power meters.

Accurate, durable, and cheap photometers do not exist. When you are able to buy the a RGB light sensor it does requires careful calibration and must be constructed from electronic boards. What these would allow is the inclusion of daylighting or the mixing of multiple fixtures into lighting calibration. Currently we set light points for specific fixtures for a rule rather than the more correct and general setting a light level for the space. This is because we do not have an easy way to measure the sum effects of all sources in a space and simulating that would be onerous. With a single point measurement we would be able to characterize and optimize energy use further.

Power meters are just becoming popular to install, but they are being installed at a course granularity such as floor, wing or building. While this does give us information about the overall state of the building we may not be able to characterize lighting costs without per-fixture or at least per breaker monitoring. While it may be possible to infer energy costs by correlating log data, a sensor-based approach would likely be a more reliable and more expedient approach. If manufacturers give accurate data for each renderable illumination point then it could be simulated in software, but the need for a feedback loop of this nature still exists.

5.2.2 Fast Fixture Colorspace Characterization

As more fixtures become tunable, manufactures will expend effort to characterize their spectral output so that the users are not required to specify channel-specific output but instead select a color and a brightness. While it is possible to directly match a point currently it is onerous to plot every possible point for a given fixture as each in our installation had 16.7 million inputs. While it is possible to characterize spectral output and sample a lesser number of points it is still a time intensive function and does not take into account shifts over time due to degradation of the fixture.

5.2.3 Mapping and Traversing the Chromaticity Gamut

The chromaticity gamut is a the two dimensional shape pictured in Figure 2.10 and it has been studied in terms of static perception, but additional data has not been routinely linked to it. The most obvious mapping to make for tunable lighting is power use as each spectrum requires a different spectral power output, correspondingly power usage, to maintain the same perceived illuminance level. When combined with color perception date we could find regions where color differences are imperceptible but results in dramatically different power consumptions.

This above example was relevant for static points, but the management of fading from one chromaticity to another is a different problem. The naive approaches are either to instantaneously jump there or to traverse a line drawn between the cartesian points. Since CIE 1931 is not distortion free this means that you could be going through regions of very perceptible color changes rather than traversing a less perceptible trajectory to arrive there. Combining the mapping thought with the concept of translation, spaces as described in Section 3.3.1 as foyer and circulation are frequently in transition states and thus we should optimize both for perception and power consumption in transition in those spaces.

Appendix A

Interface Screenshots

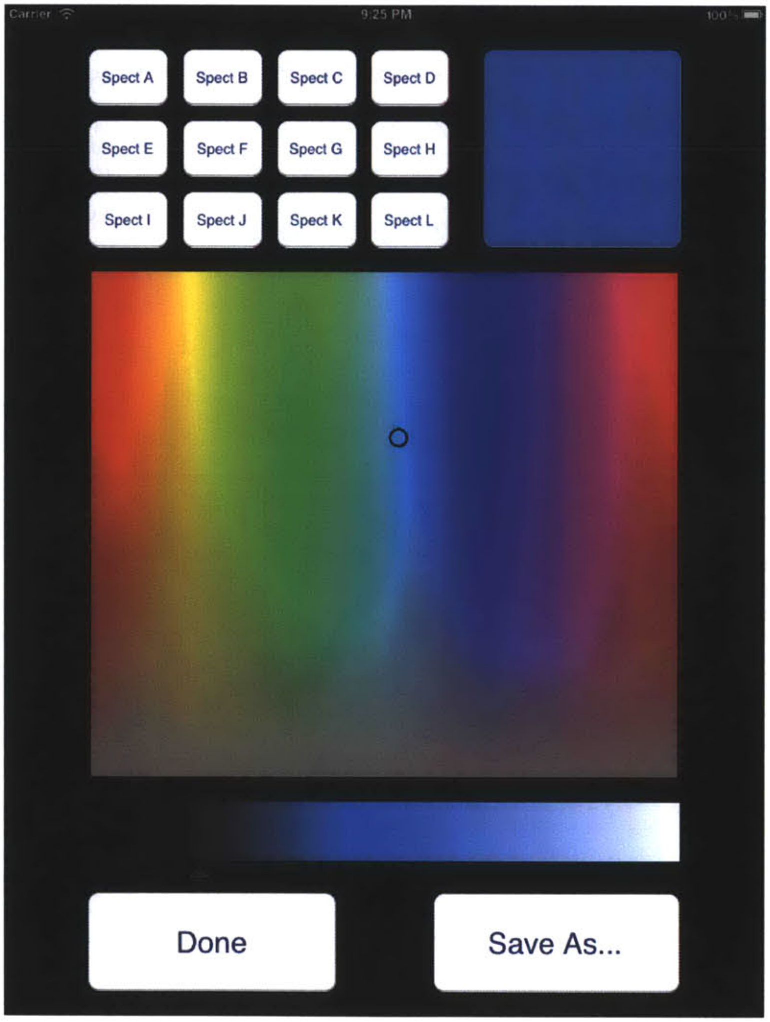


Figure A.1: iPad interface by Sean Salzberg: color picker screen

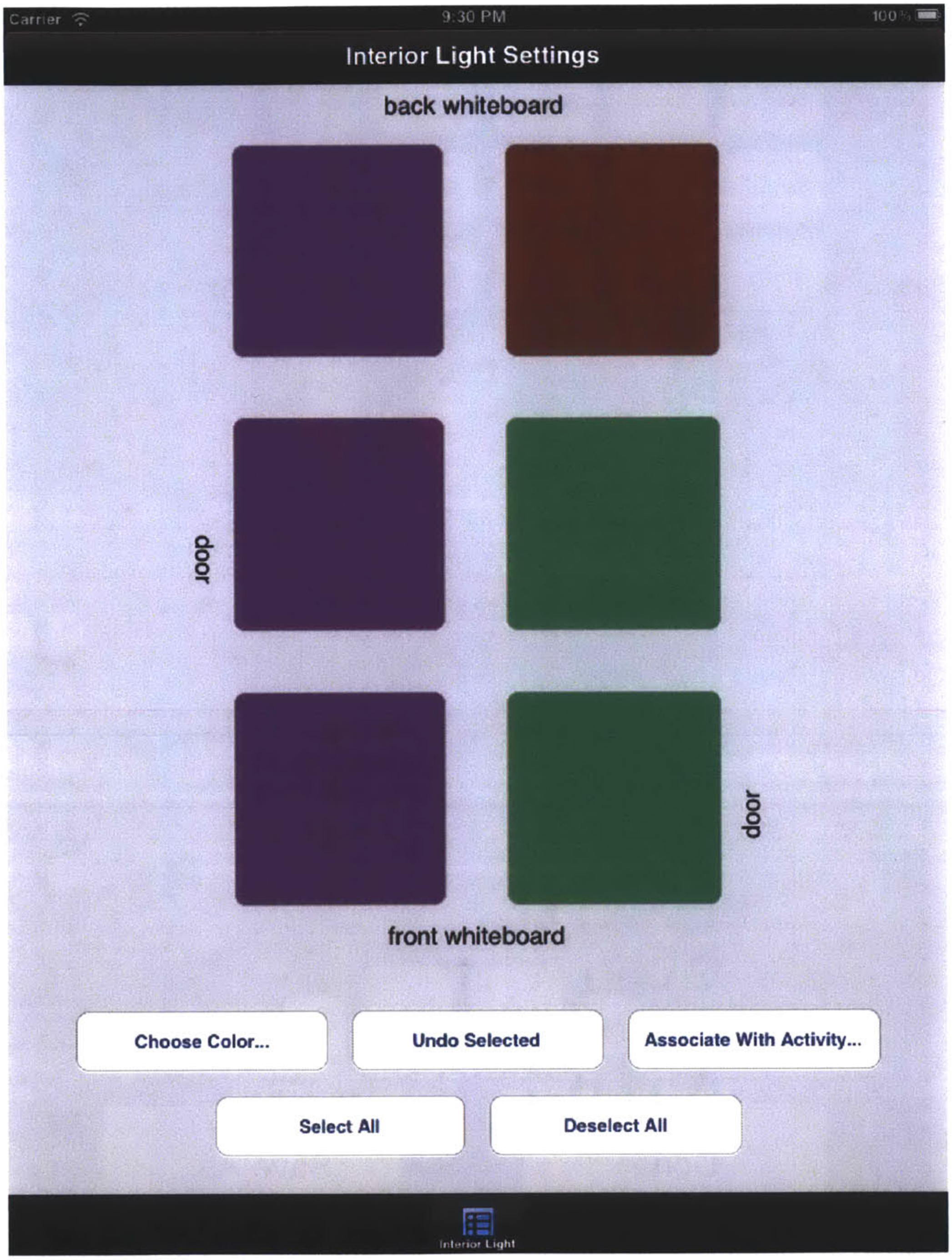


Figure A.2: iPad interface by Sean Salzberg: office installation panel select screen

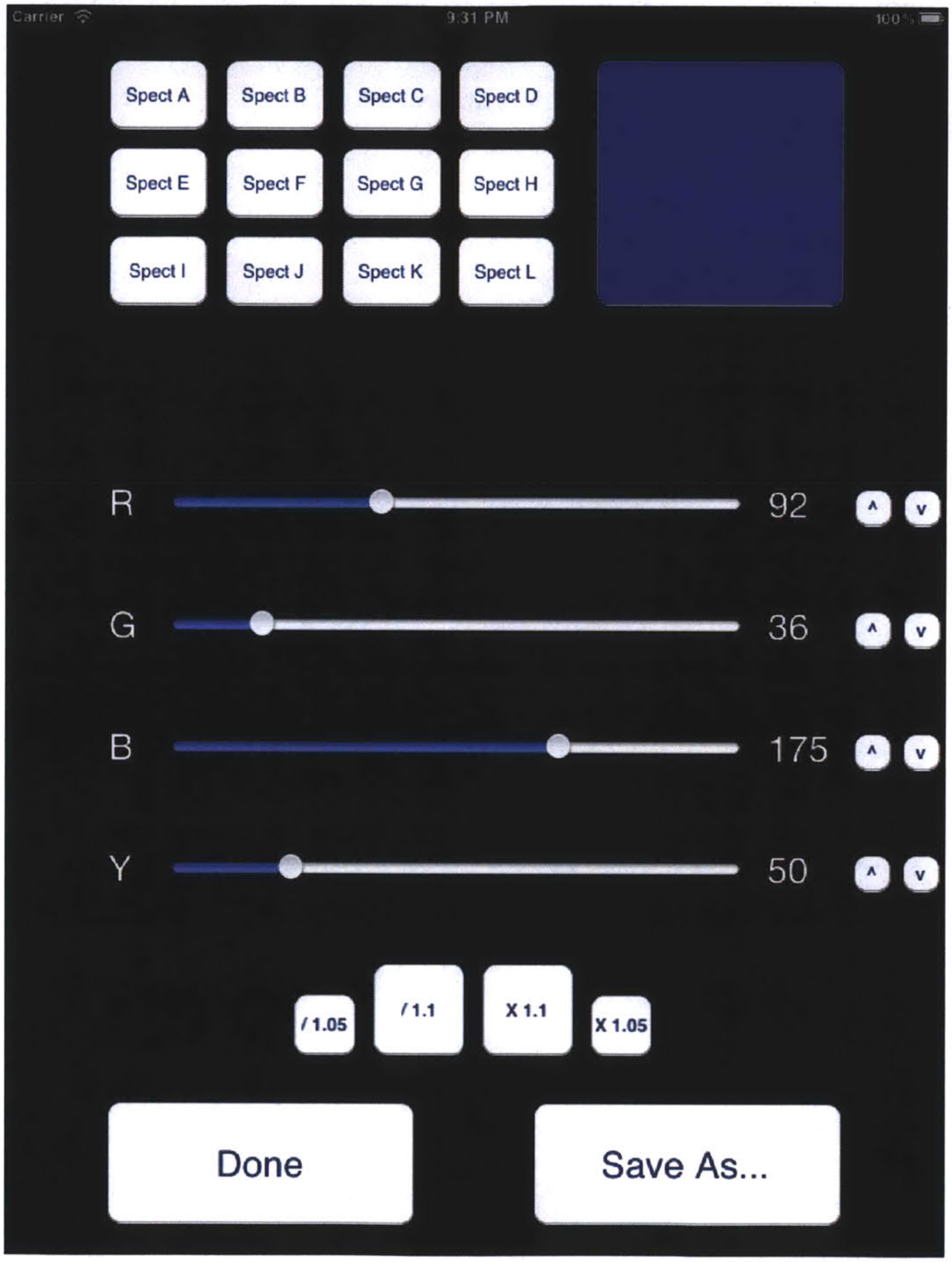


Figure A.3: iPad interface by Sean Salzberg: channel-level control screen

Appendix B

Installation Space Diagrams

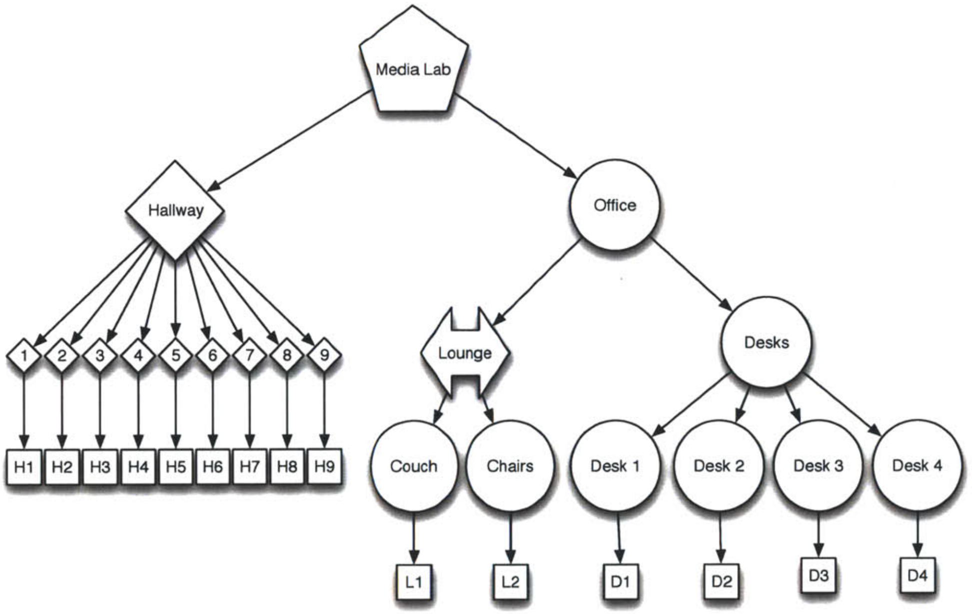


Figure B.1: Space tree subdivision of Media Lab installation. The different shapes represent different classes of space: pentagon is meta, circulation is diamond, occupancy is a circle, bidirectional arrow is a foyer. Fixtures in the space are represented as small squares.

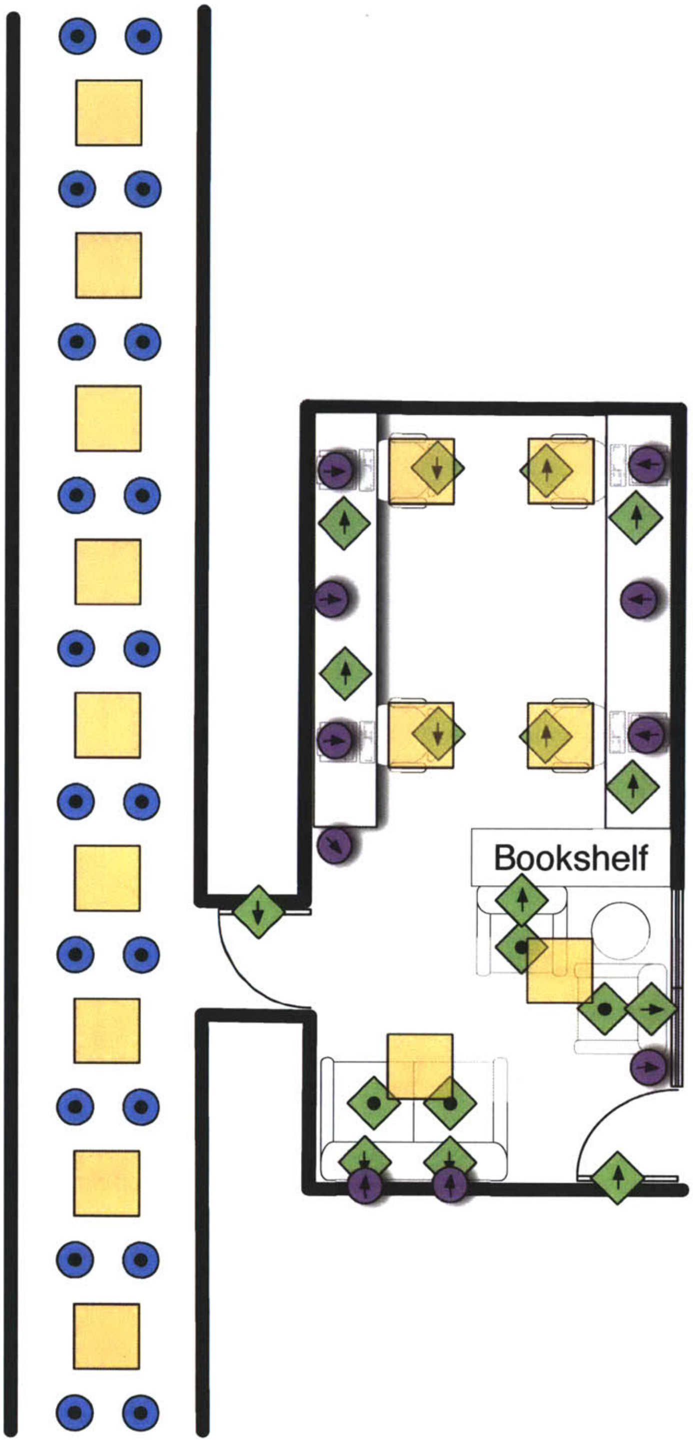


Figure B.2: Topdown layout of fixtures and sensors in corridor installation. Single-axis accelerometers are denoted by green diamonds with the responsive axis marked by the arrow. Purple and blue circles are passive infrared sensors with medium height shields that provide a field of view of ≈ 75° with an sensing range of $4m$ whose color depends on if they are mounted on the wall or ceiling, respectively.

Appendix C

Hardware Photos

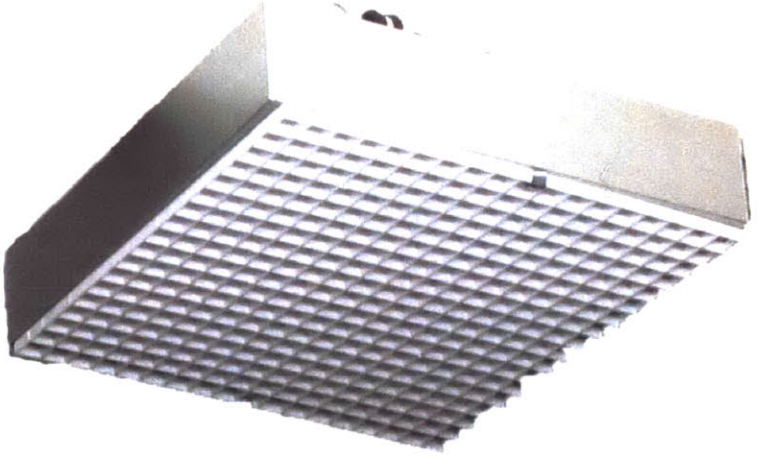
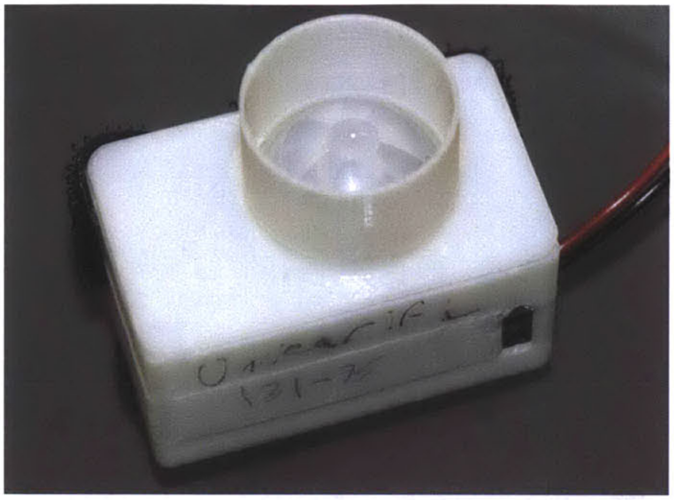


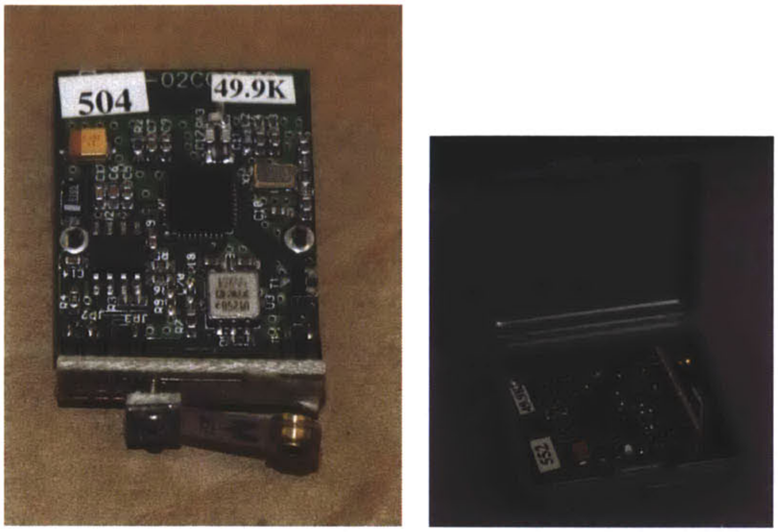
Figure C.1: OsramSylvania DMX512-Tunable LED RGBY Fixture



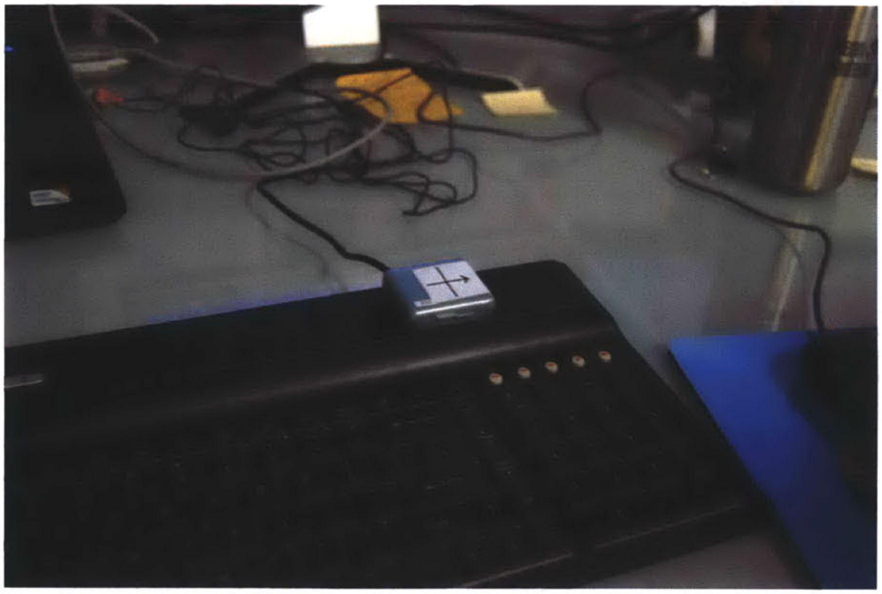
(a) PIR

(b) PIR disassembled

Figure C.2: Motion MITes installed in the implementation installation.



(a) Motion MITes Sensor (b) Motion MITes in Box

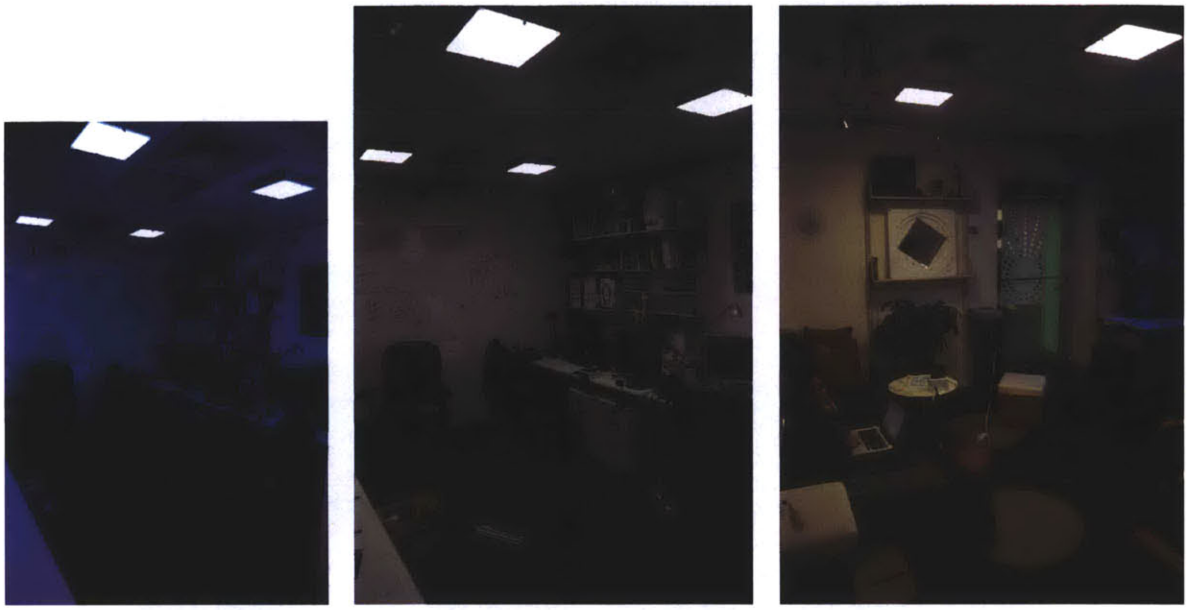


(c) Motion MITes on a keyboard

Figure C.3: Motion MITes installed in the implementation installation.

Appendix D

Installation Space Photos



(a) Workspace Unoccupied (b) Workspace Occupied (c) Lounge Occupied

Figure D.1: Photos of the office under control of Lumental under various lighting conditions

(a) System off

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