Genie: A Longitudinal Study Comparing Physical and Software Thermostats in Office Buildings

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ABSTRACT

Thermostats are the primary interface for occupants of office buildings to express their thermal comfort preferences. However, traditional thermostats are often ineffective due to physical inaccessibility, lack of information or limited responsiveness, which lead to occupant discomfort. Modern thermostat designs do overcome some of these limitations, but retrofitting them to existing buildings is prohibitively expensive. *Software thermostats* based on web or smartphone apps provide an alternate interaction mechanism with minimal deployment cost. However, their usage and effectiveness have not been studied extensively in real settings. We present *Genie*, a novel software thermostat that we designed and deployed in our university for over 21 months. We compare the use of Genie to traditional thermostats. Our data and user study show that due to the clarity of information and wider thermal control provided by Genie, users feel more comfortable in their offices. Furthermore, the improved comfort did not affect the overall energy consumption or lead to misuse of HVAC controls.

ACM Classification Keywords

H.5.m. Information Interfaces and Presentation (e.g. HCI): Miscellaneous; H.5.2 User Interfaces: Interaction style; C.3 Special-purpose and application-based systems: Process control systems

Author Keywords

Thermostat design; thermal comfort; software thermostat; HVAC energy efficiency; smart buildings

INTRODUCTION

Building occupants interact with the HVAC (Heating, Ventilation and Air Conditioning) system using thermostats to maintain thermal comfort. Since the ability of occupants to maintain control over their thermal environment has a major impact on satisfaction and productivity [37, 44], it is critical that thermostats are accurate, effective and usable. These thermostats also play a key role in HVAC operation as they complete the control feedback loop and help identify faults. Most buildings thus use common **physical thermostats**, and managers assume their use is intuitive without explicit training.

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However, a survey of 215 buildings across the US, Canada and Finland showed that 89% of the buildings do not meet thermal comfort standards [22]. Three of the top five reasons linked to occupant dissatisfaction were due to thermostats: (a) thermostats are physically inaccessible, (b) thermostats are controlled by other people, and (c) HVAC systems do not respond quickly enough to thermostat changes.

Facilities Management (FM) personnel help operate and maintain the HVAC system. They focus on occupant comfort, repair faulty equipment and energy efficient operation as the HVAC system can account for 55% of total building energy use [39]. However, thermostat use can have a significant impact on HVAC energy, but is often ignored by FM. Meier et al. [29] study various residential thermostat designs and confirm that a poor user interface (UI) and occupants' misconceptions have a significant impact on comfort and HVAC energy. Karjalainen et al [27] find similar problems in office spaces as well.

Modern thermostats, such as Nest [34], overcome several limitations of traditional thermostats. However, retrofitting them in a large building is prohibitively expensive due to installation costs and reconfiguration of the HVAC system. Retrofitting can cost $500-$2,500 *per thermostat* [14]. **Software thermostats** provide an attractive alternative to large scale retrofits [3, 16, 25]. They provide an interface to the HVAC system via a web connected device, making modern thermostat features available at a fraction of the cost.

To investigate the effectiveness of software thermostats with respect to impact on comfort and energy consumption, we designed and deployed *Genie*, a software thermostat, directly integrated with our building's HVAC system. Genie displays essential information required from a modern thermostat in a web app as well as supports features such as (i) the ability for occupants to send thermal feedback to building managers, (ii) an expanded level of temperature control, (iii) the ability to turn On/Off HVAC as needed, and (iv) estimates and displays the energy use by each thermal zone to building occupants [3].

We deployed Genie in a 5 floor university building to study its real world usage by 220 users for 21 months, and analyze the sensor data and usage logs collected. We augment our analysis with survey and interviews conducted at the end of our study to assess the usability of Genie. As far as we know, this is the first longitudinal study comparing use of physical and software thermostats in an office setting at a large scale.

Contributions and Findings

- Our participants found their offices to be more comfortable while using Genie with 45% users showing long term engagement. Clear status information and wider temperature control improved occupant experience.
- Since thermostats are not maintained once installed, they deteriorate with time. We discovered transient operational faults and extreme temperature swings in thermostats.
- Use of Genie had no significant impact on HVAC energy consumption, and did not lead to extreme temperature swings. Feedback from users assisted with identification of hard to detect faults that cause discomfort.

BACKGROUND AND RELATED WORK

Maintaining occupant thermal comfort is essential for a satisfactory [20] and productive [44] office environment, and studies show that effective HVAC control by occupants is necessary for comfort [37, 47]. Hence, thermostats and thermal comfort have been studied extensively [28, 38, 48].

Standard Building Comfort Model

The thermal comfort model followed by most buildings in the US is specified by the ASHRAE Standard 55 [45], which is based on Fanger's Predicted Mean Vote (PMV) model [17]. Fanger's PMV model considers various parameters such as air temperature, air velocity, humidity, clothing insulation and body metabolism to predict occupant comfort. The PMV expresses comfort on a 7-point scale, ranging from Hot(+3) to Cold(-3), and occupants are considered comfortable if the value is between +1 and -1. Using this model, engineers design HVAC to satisfy >80% of the occupants, and provide local control for adjustments to the temperature setting.

Discomfort in Office Spaces and Role of Thermostats

Several studies have shown that occupants are not comfortable in office spaces [22, 26, 28]. A survey by Huizenga et al. [22] shows that 89% of buildings do not meet comfort standards and list (a) hot/cold regions, (b) thermostat inaccessibility and (c) thermostats controlled by other people, as primary reasons for discomfort. Contextual interviews by Karjalainen et al. [28] found that users are unaware of thermostat availability, they do not have appropriate access, thermostats lack informative feedback, users think they are not allowed to change settings, thermostat dial is stiff or broken, and *most commonly*, users did not know how much the thermostat dial should be turned to get the desired room temperature. In a follow up work, Karjalainen et al. [27] provide design guidelines based on user studies for office thermostats that emphasizes clarity of information, adequate control, acceptable default settings, informative help and aesthetics. However, these guidelines were not tested in practice.

High Retrofit Costs of Modern Thermostats

Modern thermostats have evolved from simple mechanical devices to digital programmable thermostats, and have addressed many concerns in early designs. The latest devices even include smartphone apps, learning based schedule and energy feedback [34, 13]. However, many existing buildings have traditional thermostats installed. Our university Facilities Management (FM) estimates installation cost to be 5x the cost of thermostat, which includes labor cost for installation and reconfiguration of HVAC system. For our 466 room department building, the cost of retrofit would exceed $450K. A software only approach circumvents this problem, and promises to provide features equivalent to a modern thermostat. In addition, software thermostats are continuously upgradeable with new features or control policies.

State of the Art Software Thermostats

Several variations of software thermostats have been proposed [7, 16, 32]. For brevity, we focus on studies that performed a long term deployment. Thermovote [16] seeks to overcome the limitations of the PMV model using principles of adaptive comfort [35]. They collect occupants' comfort levels in the 7-point scale using a software interface and estimate a corrected PMV to adjust temperature settings. User satisfaction rose from 25% to 100% and 10% energy savings were observed in a five month deployment. However, the occupants were prompted every ten minutes for feedback and were not provided any information on the current status of HVAC. Comfy [41] allows occupants to express their comfort as "Warm" or "Cold" using a software app. Occupant feedback triggers a blast of warm/cool air and temperature settings are adjusted accordingly. These temperature settings are gradually relaxed to be warmer/cooler until there is another user input. Comfy's case study reports engagement of 77% of the users across six months and an energy reduction of 22% due to the relaxed setting employed when there is no input from occupants [7]. Clear et al. [8] use a similar strategy for dormitory heating systems to encourage users to save energy.

These works show the promise of software thermostats to overcome limitations of traditional thermostats. However, they force users to engage with the system while providing no informative feedback on HVAC status. Prior studies have shown that users do not engage with thermostats for long periods of time and poor mental models cause misunderstanding leading to discomfort or energy wastage [36, 52]. It is also unclear how these software thermostats co-exist with physical thermostats or how users cope when the software app is inaccessible. In addition, simplified interfaces puts the onus of maintenance on the FM, and prior studies show that they are already overwhelmed with HVAC management challenges [31, 46].

We propose an alternative design approach where occupants are provided with essential information such as room temperature and setpoints, allowing them to take control of their environment and send feedback as needed to the FM. Milencovic et al. [30] follow a similar strategy for energy and comfort feedback in offices. However, they do not allow control and no real deployments were made. We deploy our Genie software thermostat in our 150,000 sq-ft department building, and present the analysis of usage across 21 months.

Differentiation from Our Preliminary Study

Our preliminary work [3] reported usage and energy impact results from a short 5 day deployment of Genie across 65 users. The paper primarily focused on the thermal zone level energy estimation model that we integrate into Genie. In this paper, we provide a significantly deeper analysis from a longer term deployment (21 months, 220 users), based on data collected, participant surveys and contextual interviews. In contrast to our position paper, we also compare the use of Genie with physical thermostats to study their effectiveness.

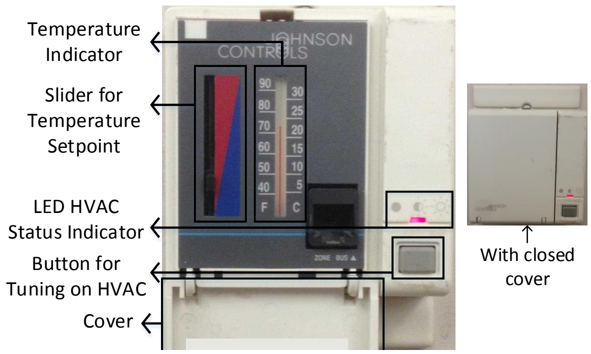

Figure 1. Thermostat used in the CSE building. Slider adjusts temperature setpoint by $\pm 1^{o}F$. HVAC power button turns On HVAC for 2 hours on nights/weekends.

Finally, we study the impact of Genie on the HVAC system and report our university FM perspectives on use of Genie.

Study of Modern Thermostats in Homes

Advanced thermostat models have been studied extensively in homes with user studies. Yang et al. [51, 52] study long term use of Nest thermostat and show automated learning fails to capture rich behavioral context and poor mental models lead to user misconceptions. Clear et al. [9, 8] advocate adaptive thermal comfort [35] and nudge users towards behavioral changes to save energy. Office environments are different from homes as the onus of maintenance and energy bills is on the FM, and the HVAC needs to simultaneously satisfy widely varying usage requirements. We focus on bridging the communication gap between the occupants, HVAC and the FM using software thermostats. With better communication, discomfort and energy wastage can be avoided by addressing over-cooling/over-heating and repairing faults in the system. We enable adaptive comfort with wide temperature control and support better mental models with informative status feedback.

HVAC Automation vs Interaction Design

Our work augments research on automation of HVAC such as occupancy based control. Scott et al. [43] use RFID tags and motion sensors, Erickson et al. [15] use embedded cameras and our own work used WiFi traces [4] for occupancy detection and control of HVAC. However, these works do not focus on interaction of occupants with HVAC system. A software thermostat like Genie would inform the user about current occupancy status so they can monitor HVAC operation.

UNIVERSITY BUILDING TESTBED

We use a 13 year old, 150,000 sq-ft. university building consisting of five floors and 236 *thermal zones* as our testbed. Each thermal zone typically consists of a large room such as a conference room or multiple small offices. In both cases, the HVAC is managed by a single thermostat. Our building uses a Johnson Controls thermostat (TE-6700 Series [24]), and the same model is installed in >50 buildings at our university. Figure 1 shows the annotated picture of the thermostat.

Notice that when the thermostat cover is closed, its functionality is somewhat unclear to occupants. Once open, we can see that it contains an analog thermometer and a slider to adjust the temperature setpoint by ±1°F. However, since there is no quantitative feedback on the effect of adjusting the slider, occupants are often unsure about its effect. Moreover, the slider range is often increased by the FM in response to comfort complaints. We observed that the change in temperature due to the slider position is non-linear and differs between zones. Thus, the user experience is inconsistent across different thermostats.

The LED on the panel indicates system status for that zone – when the LED is On (red) the HVAC is in *Occupied* mode, when blinking it is in *Standby* mode and if the LED is Off, the HVAC is in *Unoccupied* mode. In the Occupied mode, the room temperature is kept within a ±2°F bound with adequate airflow; in the Standby and Unoccupied mode the temperature band changes to ±4°F and ±6°F respectively with minimal airflow. The HVAC system runs on a static schedule: 6am - 6pm in Occupied mode, 6pm - 10pm in Standby on weekdays, and in Unoccupied mode for nights/weekends. If the occupants are in the building during off hours, they are expected to push the grey button to put the system into the Occupied mode for 2 hours. From Figure 1, we can see that these features are not apparent without prior knowledge.

Thermal Zone's Temperature Control

Temperature control in buildings can be achieved by radiant heating systems, packaged terminal units, etc. Our building uses Variable Air Volume (VAV) boxes that allow local temperature control, and VAVs are estimated to cover 20% of cooling systems and are commonplace since 1990s [23]. We base our assumptions on buildings with similar controls since new buildings and retrofits are primarily based on terminal units like VAVs. VAVs allow each thermal zone to maintain its own thermal environment by modulating the amount of (cool) airflow in the zone using a damper and reheats the supply air (hot) when necessary. Figure 2 illustrates how VAV boxes manage temperature control of each thermal zone. The Air Handler Unit determines the temperature of supply air depending on the cooling demand of the whole building. The temperature measurements of the thermostats is the only feedback to the control system. As there is only one thermostat installed per zone, even if the zone encompasses multiple offices, spaces without thermostats (e.g. Room 2 in Figure 2) cannot provide direct feedback to the HVAC system. Hence, if an occupant in Room 2 is present during a weekend, they cannot access the thermostat in Room 1. If Room 1 has high cooling demands, say due to usage of heat dissipating computers, Room 2 will be excessively cooled. This design choice is commonly made to reduce installation costs.

GENIE DESIGN AND IMPLEMENTATION

We designed Genie to overcome the limitations of traditional thermostats. Our goal is to provide transparent access to HVAC information to avoid user misconceptions. Occupants should be able to control the temperature as needed and send feedback about their comfort. We also collaborated with our university FM and ensured Genie met their requirements. With Genie study, FM hoped to reduce comfort complaints and understand the impact of occupant temperature changes. We highlight the essential Genie design decisions below.

User Interface Design

Our design was guided by prior HCI research [10, 18, 21] and the limitations of thermostats installed in our building. As noted earlier, our thermostat was inaccessible to some offices. For convenient access, we chose to implement Genie as a

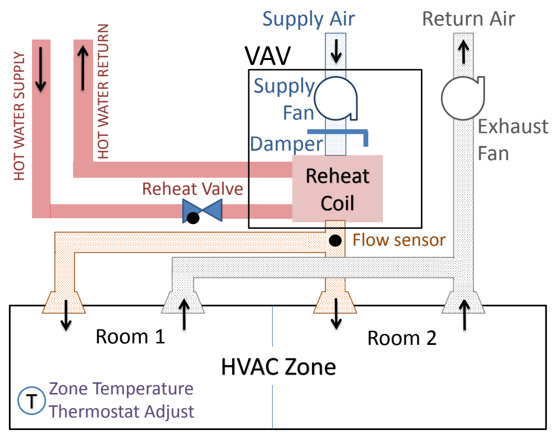

Figure 2. VAV with reheat system used for controlling the temperature and airflow of discharge air in each HVAC zone in our building [3].

web application. Figure 3 shows a screenshot of the Genie home page. It was difficult to assess HVAC status with the thermostat. In Genie, we prominently display the essential HVAC information such as measured temperature, temperature setpoint and HVAC operation status. We also show weather and historical information, which occupants find useful [29].

Applying principles of adaptive comfort [35], we allow users to modify the temperature setpoint by $\pm 3°$F. Wyon et al. [50] show that this range is sufficient to satisfy 100% of the occupants in a building. To mitigate user conflicts, we list the rooms within a thermal zone while nudging the user to be considerate of their colleagues' preferences. If a conflict occurs, we suggest that users resolve it offline as the offices in a zone are co-located. On weekdays HVAC runs on a personalized schedule (default: 7am - 7pm), while on weekends users set the number of hours they expect to be in office (1-14 hours).

We estimate the HVAC power consumption of each thermal zone (1-3 rooms) using first principles [3]. With such fine granularity power breakdown, we can analyze energy flows within HVAC and quantify impact of occupant setting changes. To improve energy awareness, we provide a personalized energy feedback to occupants [11]. We also provide comparative feedback [18] with average HVAC power for a similar sized zone and a color based visual metaphor [10, 30] from blue to red shown in a semi-circular gauge. We incorporate similar feedback for measured temperature as shown in Figure 3.

With traditional thermostats, occupants cannot express discomfort or report problems with HVAC. In our building, this led to misconceptions and many problems remained unreported. In Genie, users can express their thermal comfort on the PMV 7 point scale [17] and report details in free text. The occupant feedback is emailed to the administrator, who can directly engage with the occupant and address their concerns.

Users can request access to the rooms they have physical access to, which we manually verify before approval. Genie only takes control of thermal zones with registered users, while the rest of the zones are managed by the traditional system. The thermostat remains operational even in zones with Genie enabled, allowing users to manipulate temperature using either system. For this study, Genie was deployed in office spaces, and common spaces such as conference rooms were ignored.

FM's goal is to provide comfort in an energy efficient manner, and they attend to comfort complaints and equipment repairs regularly. With our study, FM hoped to mitigate occupant misuse such as blocking of thermostats. They wanted to study if occupant control led to increase in HVAC energy or extreme temperature setpoints. Our design and data analysis encompass these objectives. We iterated over the Genie design multiple times, incorporating occupant and FM feedback.

System Implementation

Thermostats in our building are networked together and report data to a central Building Management System (BMS). The BMS is used by maintenance personnel for monitoring and management of the HVAC system. We collect data from the BMS and store it in *BuildingDepot* [1] – a RESTful web service we developed for building data management. BuildingDepot enables control of the HVAC system, and exposes RESTful APIs for third party applications. Genie is implemented as a web service on top of BuildingDepot APIs. Separate services estimate zone-level power consumption [3] and control the HVAC settings as requested by Genie. While users mainly access Genie via web browsers, it also exposes RESTful APIs for native smartphone applications and third party services. We use the Django framework [12] to serve the Genie web application which is implemented using Bootstrap [5], and Flask [19] to deploy BuildingDepot.

Additional Features

One benefit of software thermostats is we can incorporate features in a flexible manner, similar to the Nest developer program [33]. In our initial deployment, we did not provide access to shared spaces such as conference rooms due to potential conflicts and lack of responsibility. To extend Genie functionality, we synchronized the online conference room calendar with the Genie schedule so that users can control the HVAC settings for the duration of the meeting. The HVAC is turned Off during non-meeting times to save energy.

GENIE DEPLOYMENT AND USER STUDY

Methods

We announced Genie to our building occupants on Oct 2013 over email. All occupants were invited to participate and start using Genie at any point in time. By Jun 2015, 220 users had registered on Genie. We collected sensor data from the HVAC system and logged user interactions with Genie. In addition, we recruited 32 users for an online survey and conducted contextual interviews with 9 occupants at the end of our study to understand their perspectives on Genie. Our questions focused mostly on knowledge of thermostats, comfort, features that were useful, effect of energy feedback and improvements that can be made to the system.

Users were students, staff and faculty in Computer Science, thus generally familiar with technology. Once registered, users were granted access to Genie, which provided no training or tutorial, but only general information about the goals of our system, i.e., to improve their work environment and make HVAC more effective by giving them control over temperature settings, HVAC schedule; turn HVAC on/off as needed and send feedback. Users were left to explore the features and use Genie as they wished without any particular requirement. After the initial announcement, we created an internal mailing

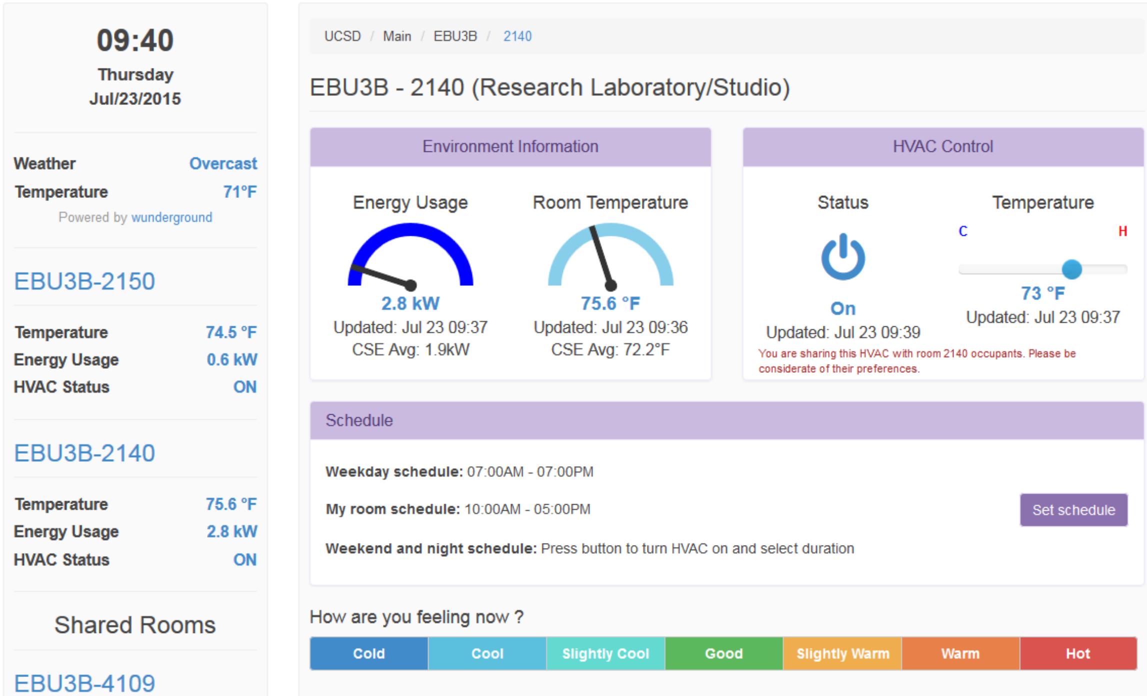

Figure 3. Screenshot of the Genie user interface. Users are given access to the rooms they have physical access to. They can change the temperature setpoint by ±3°F, choose to turn HVAC On/Off and set their own schedule.

list to inform participants about system updates. We sent three emails to announce new features over the study period.

We present our mixed-methods analysis based on sensor data and log files collected by Genie from Oct 2013 to Jun 2015, combined with the qualitative data from our 32 survey respondents and 9 interviews. All data about users' identity and the individual rooms were anonymized to protect user privacy as per our university's human research protection office's guidelines and our IRB approved study.

Longitudinal Study

We analyzed data from our 220 users and compared these with data from building office spaces constituting 152 thermal zones in our building. Each thermal zone has a physical thermostat and 82 of these zones have registered Genie users. These 82 zones are thus controlled by both Genie and thermostats while the rest of the zones (70) are controlled only by physical thermostats. To compare usage and investigate emerging patterns we start by focusing our analysis on two main features provided by both the physical thermostat and Genie: (1) change of temperature setpoint and (2) HVAC actuation during nights (7pm - 7am) and weekends.

Figure 4 shows an overview of the use of Genie and thermostats across all office zones. Note that thermostats continue to function even in Genie zones, and hence the figure indicates use of thermostats in all the 152 zones. As shown in Room 2 of Figure 2, some offices do not have thermostats. If a thermal zone only has Genie users from Room 2, but no users from Room 1, we mark this zone as *Genie w/o Thermostat*. The Genie user in this zone cannot access the thermostat, but an unregistered occupant can still use the thermostat in Room 1. There are 16 such zones in our deployment, which are a subset of the 82 zones where Genie is deployed. To better understand how the overall usage is reflected in the two different interfaces we further analyze users' behavior by breaking it down by Physical Thermostat and Genie usage.

Physical Thermostat

As none of the prior software thermostat studies compare use with corresponding physical thermostats [7, 16], we expected users to switch to Genie and use thermostats sparingly. Surprisingly, thermostats had similar usage patterns to Genie despite their usability complaints. We analyze the usage data in-depth to deduce the nuances of thermostat interaction.

Erroneous Thermostats

While manually analyzing raw thermostat data, we observed frequent and erratic changes to temperature settings even on nights and weekends. Almost all thermostats show this behavior, but some had egregious changes of $+12^oF$. The changes in settings led to unnecessary energy wastage and equipment deterioration. These erratic changes were unexpected and FM technicians confirmed that these thermostats were defective. We report these findings as they may be prevalent in other buildings and to ensure correct analysis. For most thermostats, the spurious changes were minute, and we filter them out for analyzing usage. We consider a setpoint change only when it exceeds one-tenth the range, i.e., for a thermostat with a range $\pm 1^oF$, we consider changes of $\geq 0.2^oF$. Six thermostats are marked as erroneous, and not considered for further analysis.

User Familiarity with Thermostats

74% of our survey and interview participants knew about the use of thermostat's slider to adjust temperature, and 36% knew about the actuation button for nights/weekends. Some occupants understand thermostats enough to keep them comfortable. As one of our interviewee who works regularly on weekends surmises: *"I only interact with it on weekends,*

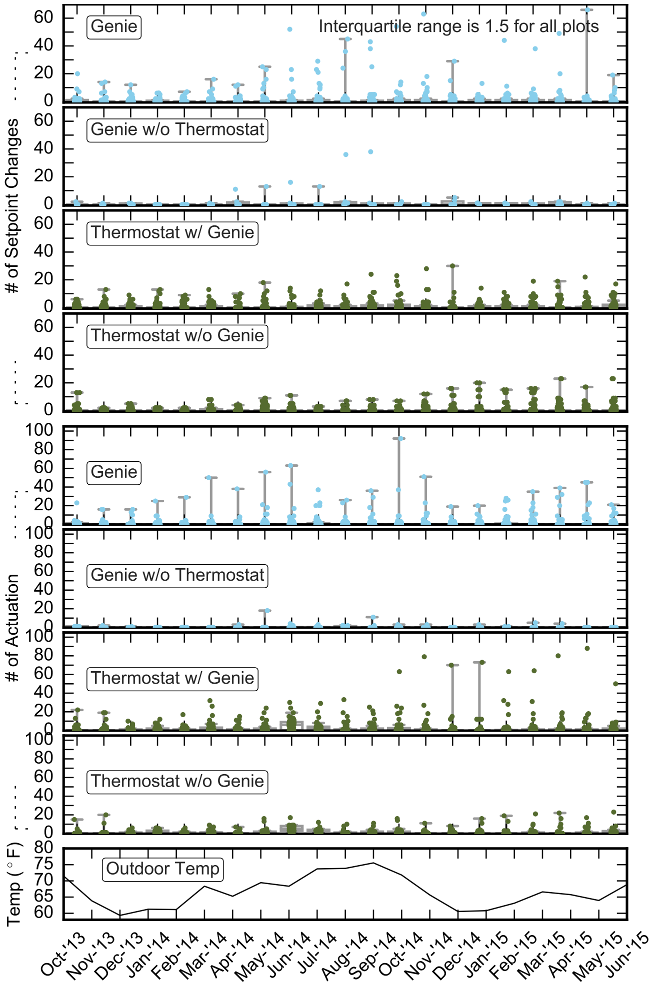

Figure 4. Comparison of temperature setpoint changes and actuations during nights/weekends across 21 months using Genie and physical thermostats across 152 office thermal zones. Genie is deployed in 82 zones. Genie and Thermostat use in these zones is shown with *Genie* and *Thermostat w/ Genie* respectively. *Thermostat w/o Genie* corresponds to 70 zones with no Genie users, and *Genie w/o Thermostat* corresponds to users in 16 zones who cannot access their thermostat.

because I figure that's when the temperature control is shut down centrally. [...] if I'm sitting still in the office for a long time and the detectors don't detect any motion I think it turns off automatically and it starts getting warmer. I have to occasionally turn it on again." In reality, the HVAC is not connected to the sensors and turns Off after two hours regardless of occupancy, but the user knew to push the button repeatedly to keep HVAC working. We also found that occupants figure out how to use thermostats over time. As another interviewee explains: *"I didn't even know you could push the button to turn on the AC at that time. So I would remember like... when I would come in on the weekends it would be hot and I wouldn't know what to do about it. [...] it wasn't until later when someone showed me how to use the thermostat and where it was even."* These interactions correlate with occasional use of thermostats in most zones.

Thermostats with High Activity

Some thermostats (15%) saw disproportionately high usage. We saw an interesting correlation across these thermostats – *in all of the cases* the temperature setpoint range was widened from the initial range of $\pm 1^o F$, and the average range was *as high as* $\pm 7.3^o F$. The range of a thermostat is extended by FM due to comfort complaints from occupants. However, these changes remain unchecked and build up over time to large ranges we observed. This change to slider range is *opaque to occupants*. Hence, when an occupant changes the slider position, they do not know the extent to which temperature changes. If the changes are extreme, they may need to adjust the slider frequently for achieving comfort. We manually inspected the data from these active zones and confirmed that occupants adjust these thermostats at least once a day.

Temperature Control and Discomfort

Our interviews revealed that occupants have several misconceptions about using thermostats and its effect on office temperature. Many participants assumed the thermostat did not work. As an interviewee states: *"I never thought it ever did anything. On the days it was too cold it stayed too cold."* Another occupant expressed frustration over its working: *"we didn't realize you had to actually push the button. I mean we were just pushing everything."*, and as a result improvised their own solution: *"Because it just blows down on me so forcefully that I actually went on top of my desk and I taped a manila folder to my ceiling."* Use of space heaters, even in summer, is also a common solution used by occupants to combat overcooling by HVAC. Such improvisations cause excessive energy waste and increases problems like overcooling. Occupants who did not have a thermostat in their offices often did not realize they had control over the temperature. As another interviewee states: *"I was freezing to death. You can shut the door if that helps. I was freezing to death and I didn't know where the thermostat was to make at least my area... at least comfortable for me."* Our surveys corroborate these findings reporting an average comfort level of 2.9 out of 5 without use of Genie.

Genie

Usage data depicted in Figure 4 shows that Genie accounts for 27% of overall usage, i.e., total setpoint changes and actuations across Genie and thermostats. The lower usage may indicate that Genie did not meet user requirements or fails to engage them. However, we recognize that Genie provides a wider temperature control than thermostats, which may result in reduced interactions as occupants are comfortable with that temperature. In addition, the physical thermostat turns On the HVAC only for 2 hours at a time on nights/weekends, while Genie expands that up to 14 hours. Thus, it is possible that Genie's absolute actuation count does not correspond to its effective usage. Our survey indicates that comfort level after using Genie increased to 4.2 out of 5 vs 2.9 using only physical thermostats, with the difference being statistically significant (one-way ANOVA, $p =< 0.0005$). We investigate how users used Genie across 21 months and the impact of our unique design features.

Engagement over time

Although Genie logs were only available for 122 of 220 users and for 13 of the 21 months due to loss of usage data logs[1], we

[1]Periods without Genie usage logs is shown in Figure 5, the data loss only affected Figure 5. The rest of the analysis uses HVAC sensor data, which are available for 21 months and 220 users.

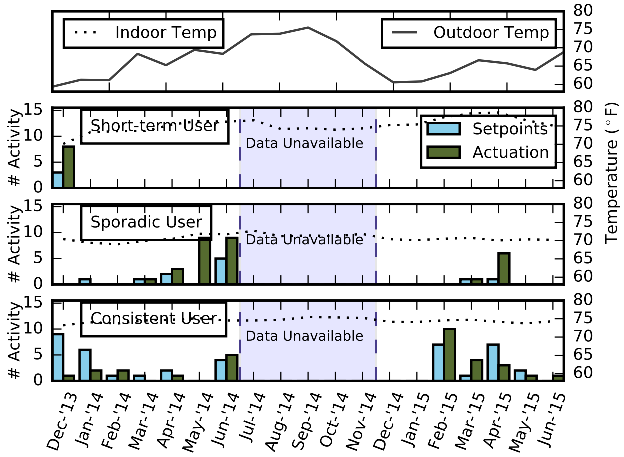

Figure 5. Genie activity comparison for representative users from each category.

still garnered a detailed view of Genie's usage characteristics. We categorize Genie's users into four types:

- **One-time (24.6%)**: Users visit the page a few times after registration and do not visit again.
- **Short-term (30.3%)**: Active use of Genie for ≤ 2 months.
- **Sporadic (23.8%)**: Usage is spread across > 2 months, but interspersed with gaps of several months.
- **Consistent (21.3%)**: Active use of Genie for > 6 months.

Figure 5 shows usage data from logs for example users from each category. A significant portion (45%) of users are in the Sporadic and Consistent category, and were actively using Genie for > 2 months. Thus, Genie served occupant requirements in the long-term, but failed to engage a subset of users.

Our interviews and survey data revealed many reasons for using Genie. It was especially useful when users could not access the thermostat. As one interviewee explains: *"I didn't actually use the older thermostat because I don't have a thermostat in this room. For me Genie is great because I have personalized access to my room."* Of the 220 Genie users, 51 did not have thermostats in their offices. Since our data does not separate users within the same zone, we identify 16 zones which only consist of users without thermostats. The "Genie w/o Thermostat" graphs in Figure 4 highlights their usage.

Users also liked the precision of control made available by Genie, as one survey respondent comments: *"Digital control of the temperature is very, very useful. Moving the slider [on the thermostat] still leaves a lot of uncertainty as to what exactly will happen, and the temperature setting helps."* One of the survey respondents commented on how temperature control affected his productivity: *"Genie is awesome and has made a real difference in my ability to work in my office. I get migraines that are correlated with higher temperatures, and Genie allows me to set the office temperature to 67, which greatly reduces occurrence."*

For the **consistent** users we found that Genie is actively used because offices are uncomfortable on a regular basis. As one user says: *"I generally think its fine ... only in the late afternoon I have to make it cooler"*. While the **sporadic** users use Genie occasionally because offices are already quite comfortable. As an interviewee reports: *"I mean, I haven't used it a lot. I just...uhm...will change the temperature if it's like too hot or too cold. And on the weekends if I'm working here I'll turn it on because the AC doesn't turn on automatically."*. **Short-term** users often indicated how the initial interest was high and then it vanished with time: *"I used it frequently at some point as in usually over the weekend, I would tweak the temperature through the web interface. Then nowadays I don't come in as often in the weekends. So if I do come, I might set up the thermostat manually coming in the room. Then usually I don't have to deal with it until I leave...so yeah, I may not have been used the web interface for a while now."*. Finally, **one-time** users typically forget the URL, or the password, and do not visit the web page after their registration. As one user indicates: *"It looks pretty friendly. It's more of a matter of out-of-sight, out-of-mind."* Our analysis of data showed no correlations between usage and internal/outdoor temperature fluctuations.

Dual Thermostat Usage

Many survey respondents revealed they use the physical thermostat despite having a Genie account. One reason echoed by several users was the thermostat provided easier access compared to opening a laptop and change settings via the web app. As one user says: *"I don't have to pull up the web interface. It's just a dedicated slider on the wall, which is pretty easy for occasional tweaks."* Similar pattern was observed with Nest thermostats [51]. Another reason was that occupants were confused about the relationship between Genie and the thermostat on the wall. As one survey respondent explains: *"I don't quite understand how the physical thermostat and Genie interact and so I often adjust both."* Both Genie and the thermostat were functional, but Genie does not directly reflect the changes made through the thermostat slider. Having access to both controls confused some users; we realized that this is a design flaw and we are planning to address that in future designs, with the Genie interface directly reflecting the physical thermostat changes.

Thermal Feedback from Occupants

While prior work used occupant thermal feedback to modify HVAC settings [32, 16, 7], we let users manage local HVAC settings and used feedback to assess HVAC efficacy. User feedbacks constitute 6% of Genie interactions, with the rest being temperature setting or actuation changes. Thus, users managed their HVAC settings majority of the time. As per ASHRAE Standard 55 [45], perceived user comfort should be within [-1, 0, +1] on a scale of -3 (Cold) to +3 (Hot). Of the 305 feedbacks, 62% were outside the comfortable range.

Each of the feedback is emailed to the Genie administrator to encourage engagement with the user and resolve issues. The feedbacks were used for a variety of different purposes. Majority of the feedbacks (77.7%) corresponded to users expressing their general discomfort or justifying their change of control settings in Genie. As one user explains: *"Felt cool for the past 1-2 wks. Just tried changing the room temp from 73 to 75 hoping we feel a difference!"* 4.6% of the feedbacks corresponded to user misconceptions on use of Genie or HVAC. For instance, this user was unclear about manual activation on weekends: *"AC seems to be off during weekend. Can I/anyone turn it on?"*

Some users expressed discomfort during a Demand Response (DR) event, where the HVAC is switched to Standby mode when grid demand is too high [2]. Without Genie, DR events are opaque to users and their discomfort is not captured.

17.7% of the feedbacks received led to fault identification in the system. Some feedback comments explicitly described the fault. For example, one user identified that their thermostat was not reporting data correctly to HVAC (and hence, Genie): *"Genie says it's 73.2 but out wall thermostat says its about 78. It definitely feels hotter than 73.2 and it is quite significantly cooler just outside in the hallway. Is the Genie temperature sensor broken?"* Other feedbacks led to fault detection after conversing with the user. We identified 30 faults during our study. Examples include: thermostats blocked by computers, dampers getting stuck, HVAC misconfiguration, etc.

Our FM was pleased with the Genie feedback feature for three reasons: (1) User feedbacks are a small proportion of HVAC setting changes, which translates to less number of comfort complaints[2]. (2) FM does not have the manpower to inspect each room for faults. The feedbacks help to precisely identify these faults. (3) The feedbacks reveal the general comfort issues in the building. Further analysis revealed that 56% of uncomfortable feedbacks (i.e. outside range of [-1,0,+1]) belonged to users consistently reporting overcooling/overheating issues. This information can be used to tune the HVAC system to provide better comfort.

Energy Feedback to Occupants

We provide energy feedback in Genie to raise awareness on HVAC energy footprint. Our preliminary study over a 5 day deployment was promising, with many users appreciative of the energy information and we observed 5% reduction in HVAC energy in Genie zones [3]. With this 21 month study, however, we observed no significant difference in overall energy consumption between Genie and non-Genie zones.

The survey revealed that users were divided on whether they were more energy conscious after using Genie, with a mean score of 2.8/5. Many users commented that their comfort was a clear priority over the energy consumption. As one interviewee states: *"If I'm hot dude...I'm going to turn it on. I mean uh...I got work to do. You know...if I got to use a little bit of wattage I don't care."* Some users agree that it is good to be aware of the energy consumption, but it does not change their behavior in any way. As one user comments: *"I do care, but admittedly would do whatever I needed to be comfortable without regard to energy consumption."* A subset of users, however, expressed a desire to better understand their energy footprint, and wanted more indication in the interface on how they could act upon decreasing it. One user states: *"I think it would be helpful even to see what your peers...what their energy consumption is. Just to kind of see if I'm conserving a lot more, or...wow...I'm way over the top. Maybe I need to start being more conscientious about things."*

38% of the users said that they were more energy conscious after Genie feedback. Therefore, the energy feedback does

[2]We do not have data to directly compare the Genie feedbacks received with number of complaints FM receives from occupants.

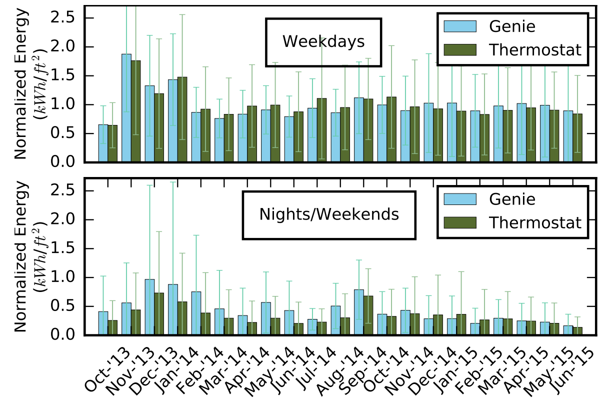

Figure 6. Energy consumption of 82 Genie zones and 70 Thermostat zones across 21 months. The energy consumption has been normalized by area to account for varying room sizes. Other confounding factors such as presence of windows is assumed to be randomly distributed.

seem to have an impact on a subset of our user base. We will explore methods to make energy interventions more effective using methods proposed in HCI papers [6, 52] in future work.

Conflicts in User Preferences

We observed only a few conflicts during the study. Users sent comfort feedback about conflicts when they did not understand that the thermal zone could span multiple rooms. The administrator clarified the concept of a zone when such misconceptions occurred and the occupants would resolve conflicts among themselves. There were some conflicts in which the users could not come to an agreement. In a few cases, one of the rooms in the zone hosted a machine that generated heat, which led to overcooling of the adjacent room. In the latter two cases, the administrator explained the conflict to the occupants and asked them to come to an agreement.

Genie's Limitations

Despite the overall positive feedback, Genie introduced its own set of problems and exposed some limitations. A common issue among users was that the HVAC control was limited to once every 10 minutes. This was a design decision in collaboration with FM to protect the HVAC equipment from excessive use. As a consequence of this conservative setting, Genie was unresponsive to specific user behaviors and intended interactions with the system. As one user explains: *"I was trying to adjust it and I moved it down and I slipped, and so I let go of the mouse and it only moved a half degree. Then it was like you can do this again in 10 minutes'.* Another issue occurred when Genie was unavailable due to maintenance. We have had only a few instances of unavailability over some weekends, and at that time users had to revert to using thermostats. One user sent us a message when Genie was down: *"For some reason the A/C wasn't running ... I don't have a thermostat in my office (it's in another office next to mine that I don't have access to), so genie was my only hope".* Hence, an alternative failsafe mechanism such as a manual thermostat override is necessary in case occupants cannot access a networked device or in case of failure events.

IMPACT ON THE HVAC SYSTEM

As Genie provides more flexibility for occupants to control their temperature and turn HVAC On/Off, one of the risks from our FM's perspective was that Genie could lead to increase in energy consumption or deviation of operation from HVAC's original design. To investigate the impact of Genie usage on HVAC, we compare the energy consumption and the extent of control exercised using Genie versus thermostats. We denote 82 zones where Genie is deployed as *Genie* and the remaining 70 as *Thermostat* zones.

Energy Consumption

Figure 6 shows a comparison of normalized energy consumption for weekdays and weekends separately in Genie and non-Genie zones. The weekday graph indicates that the energy consumption of Genie zones is comparable to the thermostats. Overall Genie zones save 3.5% energy, but considering variance in values, the difference is statistically insignificant (Welch T Test,p=0.97). On the weekends, Genie zones consume 31.6% more energy on average but the difference is again statistically insignificant (Welch T Test, p=0.11). Genie provides a slider to turn On HVAC for up to 14 hours, whereas thermostat button only turns On HVAC for 2 hours. The increase in energy in Genie zones on weekends could be attributed to: (i) Users not using thermostats on weekends, and hence their comfort requirements are unmet. (ii) Users overestimating their stay time in Genie, thus providing comfort but wasting energy. From our data, the average HVAC use on weekends/nights was 4.75 hours using Genie. We do not have data to confirm occupancy periods, but 4 to 5 hours is commensurate to expected stay time on weekends and far lesser than maximum limit of 14 hours on Genie. We hypothesize that users set the slider as per their estimated schedule.

Comparing the energy consumption across weekends and weekdays, Genie zones consume 3.4% more than thermostat zones on average, but the difference is again statistically insignificant (Welch T Test, p=0.49). Therefore, the long term use of Genie has not had a significant effect on HVAC energy.

Temperature Swing

As the temperature setpoint can be changed by 6°F (i.e., ±3°F) in Genie, users may change the setpoint to its extremes which can lead to excessive energy consumption or large swings in airflow. We compared the variation in temperature settings across all zones as shown in Figure 7. Surprisingly, some physical thermostats show more deviation than Genie, with up to 6°F standard deviation. These can be attributed to thermostats whose range have been increased by FM in response to past comfort complaints. 63 of the 152 thermostats had a slider range larger than the designed ±1°F, and the FM does not keep track of these range changes. In contrast, despite having the freedom to change temperature by 6°F in Genie, the most extreme changes in Genie are $\sim$ 4°F. The standard deviation for changes in Genie is ±2.0°F, compared to ±3.5°F in thermostats, and the difference is statistically significant (one-way ANOVA, $p < 0.0005$). Hence, we observe that providing users more control with clear status feedback results in better comfort and has minimal impact on HVAC compared to thermostats with an opaque slider without feedback [27]. Our university FM was surprised with the large deviations caused by cumulative changes to thermostat ranges, and the effectiveness of status feedback in managing user behavior. They seek to implement measures that improve thermostat feedback in other campus buildings.

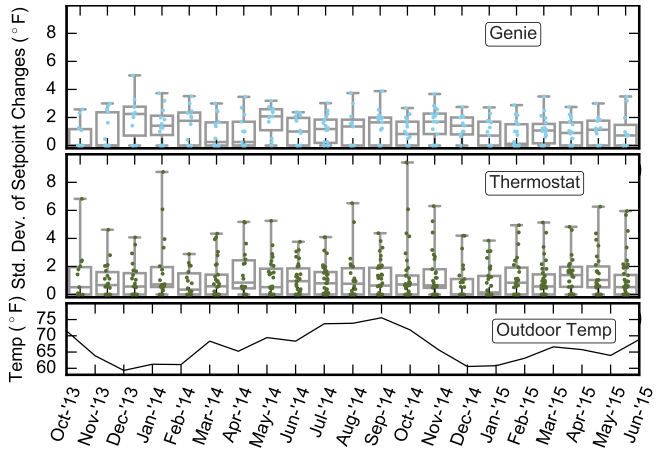

Figure 7. Change in temperature setpoint using Genie (82 zones) and physical thermostats (70 zones) across 21 months. The whiskers of the box plot indicate max-min variations in setpoint changes.

Facilities Management Perspective

Before Genie study, our university FM policy was to provide limited control to occupants as it was easier to operate the HVAC system efficiently. The thermostats were given a wider range upon complaints from occupants. However, FM receives a large number of occupant complaints, and even a minor complaint takes valuable time away from addressing important issues such as fixing faults. Thus, the university FM funded our research to explore solutions that improves user comfort.

We presented the summary of our study to the FM. They were surprised that poor thermostat usability could lead to many occupant issues and that thermostat ranges widened significantly with time. They appreciated that Genie could address many occupant concerns, and negated occupant caused problems such as blocking of thermostats or use of space heaters. Even if Genie did not reduce energy consumption, it saved FM from time spent in resolving occupant misconceptions and minor complaints. FM personnel were happy with the results and would like to deploy Genie in all our university buildings.

REFLECTIONS ON SOFTWARE THERMOSTAT DESIGN

Our analysis of thermostat's and Genie's usage data with user interviews and surveys reveal that thermostats in our building fail to provide clear status and feedback information. These findings confirm the outcomes of prior studies [26, 28]. We showed how software thermostats can alleviate these issues and provide additional features such as getting occupant feedback.. From our experience with the design of Genie and our user study, we reflect on the lessons learned and trade-offs in design choices of the software thermostat.

Design Lessons

- **Relationship to Physical Thermostats:** Instead of supplanting physical thermostats, they can be used to provide basic functions and act as a failsafe alternative for software thermostats. The physical and software interfaces should be similar and synchronized to avoid user confusion.
- **Clarity of Information:** Precise information allows user to better comprehend what the HVAC system is trying to accomplish. The interface should be designed to promote correct mental models. Users visit the software interface

when they are uncomfortable, and accurate information allows them to infer the status quickly.
- **Provide Adequate Control:** Users liked the ability to control their office HVAC. Showing users the control available and its impact on HVAC enables intelligent use. Our data shows that users are careful with controls and the impact on HVAC is minimal. But, the design needs to prevent misuse of control. Our design limits the control (e.g. $\pm 3°$F temperature changes, 10 mins lockouts) based on FM's advice.
- **Feedback to Building Managers:** Comfort feedback provides FM with information on occupant comfort level and helps in identifying faults such as thermostat blockage. The crowd-sourced comfort information also acts as feedback for control strategies like Demand Response.
- **Hide Physical Characteristics for Usability:** Users expect fast reaction times in a software interface. The system needs to hide HVAC latency and show the predicted behavior due to a change in setting [42]. Also, users should be able to correct mistakes, like "Undo Send" in Gmail [49].

Simple Feedback Based Control vs Direct User Control
Software thermostats like Thermovote [16] and Comfy [41], ask for comfort feedback from users (Warm, Cool, etc.), and control HVAC. However, they need frequent user feedback to profile comfort requirements accurately, and hence their interface forces the users to give feedback. In contrast, a Genie user can have no interaction for months at a time as comfort is maintained based on thermal bounds defined by the PMV model [45]. User comfort is maintained in both the interfaces, but a Genie user need not continually give feedback.

Energy Consumption vs User Comfort
Comfy and Thermovote report significant energy savings. The HVAC system needs to spend a certain amount of energy to maintain comfort, and energy savings indicate that the HVAC system was initially overcooling/overheating the office spaces. Thus, both comfort and energy savings may have been achieved because of this initial poor tuning of the HVAC system. We tuned our building HVAC for efficient operation in Feb 2014 (see our technical report for details [46]), and hence, a lack of energy savings is not surprising.

We can design the interface to challenge the notion of guaranteed comfort as exemplified by the temperature drift mechanism used by Comfy and Clear et al. [8]. However, there is a tradeoff between user productivity and HVAC energy. As Pierce et al. [40] point out, strategies that cause enough discomfort to users do not get adopted in the long run. Using physical thermostats, our university FM imposed a similar restriction on user with $\pm 1°$F range on thermostats. When users get annoyed, they circumvent the restrictions in place and eventually lead to more energy consumption or even damage to the system as exemplified by use of space heaters and blocking of the HVAC vent in our study.

Automation vs User Interaction
As our sensing capabilities improve, we can create systems that automate many aspects of HVAC. Occupancy sensors can detect presence and body sensors can detect comfort. However, as shown by Nest studies [51, 52], user context has many dimensions and it is difficult to precisely determine user intent in all situations. Further, there may be times when the automation system fails. In such situations, it becomes necessary for the user to interact with the system. Thus, it is essential that the HVAC system exposes an interface that encourages a good mental model and makes it easy for a user to understand the status. The interface also needs to provide easy to use "knobs" that allows user to specify their intent. Lack of a good interface leads to misconceptions, which can lead to detrimental effects such as damage to equipment, or energy wastage.

University FM have limited time and resources to address energy efficiency of the HVAC system. There are many well established methods to conserve energy in HVAC systems – automated and continual fault diagnosis (up to 20% energy savings), occupancy based control (up to 40% savings), automated demand response, etc. Thus, the software thermostat needs to be low cost while simultaneously satisfying users so as to reduce complaints that the FM needs to attend. A sophisticated automation system without significant benefits becomes an additional burden on the FM.

Limitations
We note that our study of physical thermostats and Genie usage has been conducted in a university building located in a temperate climate zone in the US. The analog thermostat we studied is from Johnson Controls, a popular vendor who installs HVAC systems across 125 countries. Although the thermostat model we consider is installed across >50 buildings in our university campus, it predates the latest digital model provided by the vendor. Therefore, more research is needed to verify our findings across different cultures, climate zones and types of thermostats. Finally, our occupants are all from a Computer Science building, and more research is required to generalize our findings to other population pools.

CONCLUSION
Multitude of buildings today use poorly designed, outdated thermostats that provide limited control and lead to occupant discomfort. Modern thermostats overcome several drawbacks of older thermostats, but their retrofitting cost in a large building is prohibitive. We designed Genie, a software thermostat for office buildings that incorporates features of modern thermostats. In addition, Genie includes HVAC energy information and lets users send comfort feedback. We deployed Genie in a 150,000 sq-ft. university building, and analyze usage across 21 months. 45% of users showed long term engagement with Genie, an additional 30% users showed short-term engagement and users reported improved comfort compared to using thermostat alone. Comfort feedback from users led to detection of 30 faults and clarified occupant misconceptions. The improvements in comfort had minimal impact on HVAC energy and operational settings.

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