Thermal Model and HVAC Control White Paper

Introduction

At Nest, we believe in continually improving our products. To do so, we use our software update technology to improve the performance of products already deployed in people's homes. In fall 2015, Nest updated all connected Nest thermostats to a new software release, version 5.1 with two significant improvements: a new home thermal model and new HVAC control algorithms.

Nest's home thermal model predicts the future temperatures inside a home based on the weather, current state of the home, and HVAC state. This new version of our home thermal model drastically increases the number of homes with well-performing models and improves prediction accuracy for all homes compared to our previous model. Better temperature predictions improve features such as Time-to-Temperature and Early-On.

HVAC Control 2.0 uses the new home thermal model to choose better HVAC control strategies (when to turn on/off your heating/cooling equipment) on the thermostat to optimize comfort and HVAC energy usage, providing significant additional savings for multi-stage and heat pump systems compared to Nest's previous controller. In addition, the new HVAC 2.0 controller maintains the indoor temperature closer to the target temperature than before. Both of these features personalize the modeling and control of the thermostat to individual homes and systems, improving comfort and efficiency for users.

Highlights:

- Nest's home thermal model predicts the temperature inside the home at any future time based on the weather, current state of the home, HVAC state, and other inputs.
- The thermal model is used for features such as Early-On, Time-to-Temperature, Heat Pump Balance, Rush Hour Rewards, True Radiant and HVAC Control.
- For all systems, the new home thermal model improves Nest's ability to accurately predict the indoor temperature one hour in the future relative to the previous model. In addition, it also increases by 60% the number of homes with very accurate thermal models relative to the previous model.
- HVAC Control 2.0 uses the new home thermal model to find the optimal HVAC control for each individual home. In homes running multi-stage or heat pump HVAC systems, HVAC Control 2.0 can achieve incremental savings: our simulations predict incremental HVAC energy savings of 3.8% for multi-stage heating systems, 6.5% for heat pump systems, and 5.4% for multi-stage cooling systems (all when compared to the previous controller).
- HVAC Control 2.0 also maintains the temperature up to 20% closer to the target temperature for all systems, compared to the existing pre-2.0 HVAC Controls

Thermal Model

What it is

The home thermal model is one of the core technologies on the Nest thermostat. It allows the thermostat to learn how quickly a house warms up and cools down over time, under varying external conditions. Because no two houses are exactly the same, these characteristics tend to vary a lot across different houses. For example, if your house is well insulated and it is cold outside, the heat will be retained for a much longer period of time than for a home that is very leaky. Nest uses state of the art machine learning algorithms to determine the thermal properties of each home individually. And once the thermostat understands how the house warms up and cools down, it allows it to keep users much more comfortable while maximizing their energy savings.

Predictions of the temperature inside a house are used by several features on the Nest Thermostat that are important to both comfort and energy savings. Examples of these features are: Time-to-Temperature (a prediction of when the target temperature will be reached), Early-On (a feature to begin heating or cooling the home in advance of an upcoming setpoint so that the home is at the temperature you want at the time you want it), True Radiant (a feature that enables better scheduling and avoids over-shooting temperatures often associated with radiant heating systems), Heat Pump Balance (a feature that balances the use of faster-but-more-expensive auxiliary heating with slower-but-less-expensive heat pump heating), Rush Hour Rewards (a feature that that helps you earn money back from your energy company by using less energy when everyone else is using more), and HVAC Control (which will be discussed in more detail later in this white paper). All of these features benefit from knowledge of how the temperature in the house responds to the HVAC system as well as the outdoor weather and humidity.

With the new home thermal model, Nest has improved its ability to predict the home's temperature at a point in the future. This means that the existing features on the Nest Thermostat that use the thermal model are also improved because of this update, thus improving the overall user experience.

How it works

When learning the thermal model for a house, the algorithm uses sensor observations provided by the Nest Thermostat. Among other things, the thermostat measures the temperature and humidity inside the home throughout the day, as well as the state of the HVAC system. Additionally, the thermostat gets information through the Internet about the weather conditions and outdoor temperature from weather stations that are in the same area.

Using all this data, Nest then utilizes sophisticated machine learning techniques to build a model that captures the thermal dynamics inside the house. This is done uniquely for each house based on that house's data, and no two homes have the same thermal model. One of the biggest challenges is that Nest doesn't have any knowledge about the characteristics of the house such as the size, layout, leakiness, HVAC system, or thermostat location. Without knowing these characteristics, the thermostat must predict the indoor temperature accurately just by looking at how the temperatures and humidities inside and outside the house change over time.

Our solution to this problem is to build a model inside a model. The inner layer of the model captures the internal dynamics of the house, whereas the outer layer captures how the house interacts with external conditions (e.g. the weather and HVAC system configuration) and how it drives sensor observations (e.g. the indoor temperature and humidity). By introducing this separation, we are able to learn accurate models for many different types of houses. An overview of this new modeling strategy can be found in Figure I.

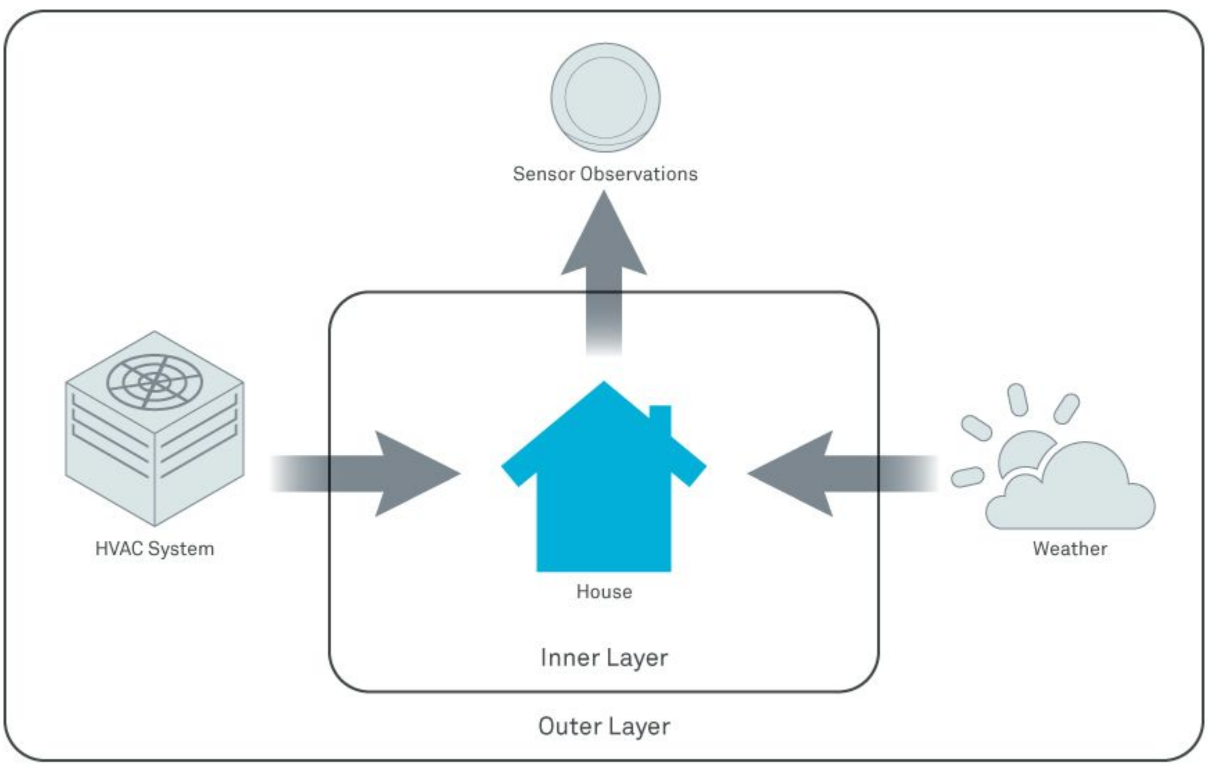

Figure I: Schematic overview of the two separate layers in the new thermal modeling strategy.

Results

Case study

One of the core metrics we use to assess the performance of our home thermal model is how well it is able to predict the indoor temperature at some specific point in the future. If we can accurately predict the home's future temperature, we can do a better job controlling it to precise requirements. In Figure II we look at an example of the new thermal model and the previous model predicting the indoor temperature for a house in Austin, Texas during the summer. Both models provide accurate future temperature predictions, but the improvements of the new model can be seen.

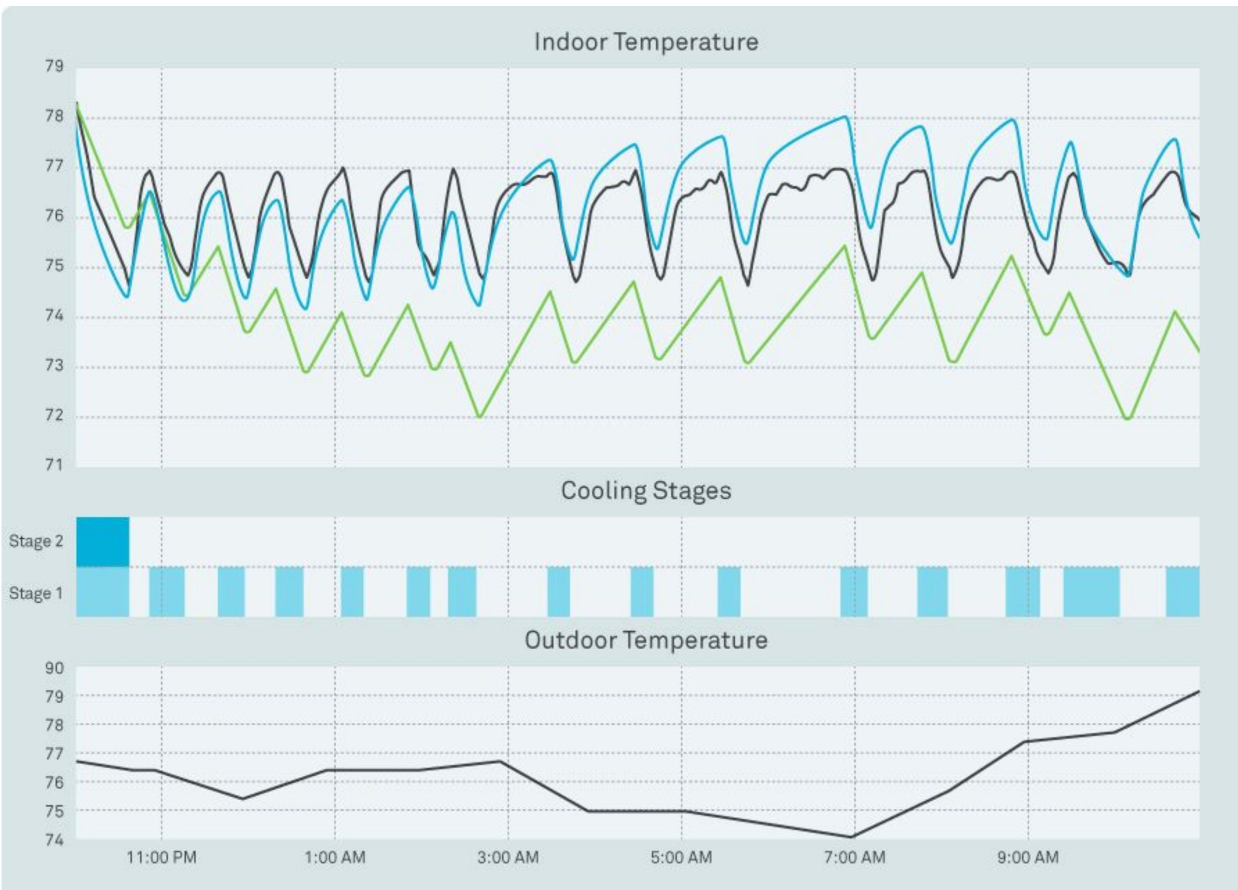

Figure II: The predictive performance of the new home thermal model (blue line) versus the previous model (green line) evaluated against the actual indoor temperature (black line).

Average results

In addition to the case study, we show how the model's one-hour ahead temperature predictions compare with the previous model. In this context we look at the prediction accuracy for a random set of 1000 houses with heating systems during the winter (Figure III), and 1000 houses with cooling systems during the summer (Figure IV). These plots show a histogram of the average prediction accuracy (difference between prediction and actual temperature) in predicting the indoor temperature one hour in the future for both models on both heating and cooling systems.

For heating systems, the number of homes with highly accurate thermal models (prediction accuracy better than 1.8 ℉ per hour) is increased by over 60% compared to the previous model. Similarly, for cooling systems, the number of homes with highly accurate thermal models (prediction accuracy better than 1.8 ℉ per hour) is more than doubled. In addition to increasing the number of highly accurate models, all homes see improvements in the prediction accuracy compared to the previous thermal model. Using these more accurate predictions of a home's thermal conditions, we have developed a new feature called HVAC Control 2.0 that is better able to precisely hit desired comfort settings without expending extra energy to hit those targets.

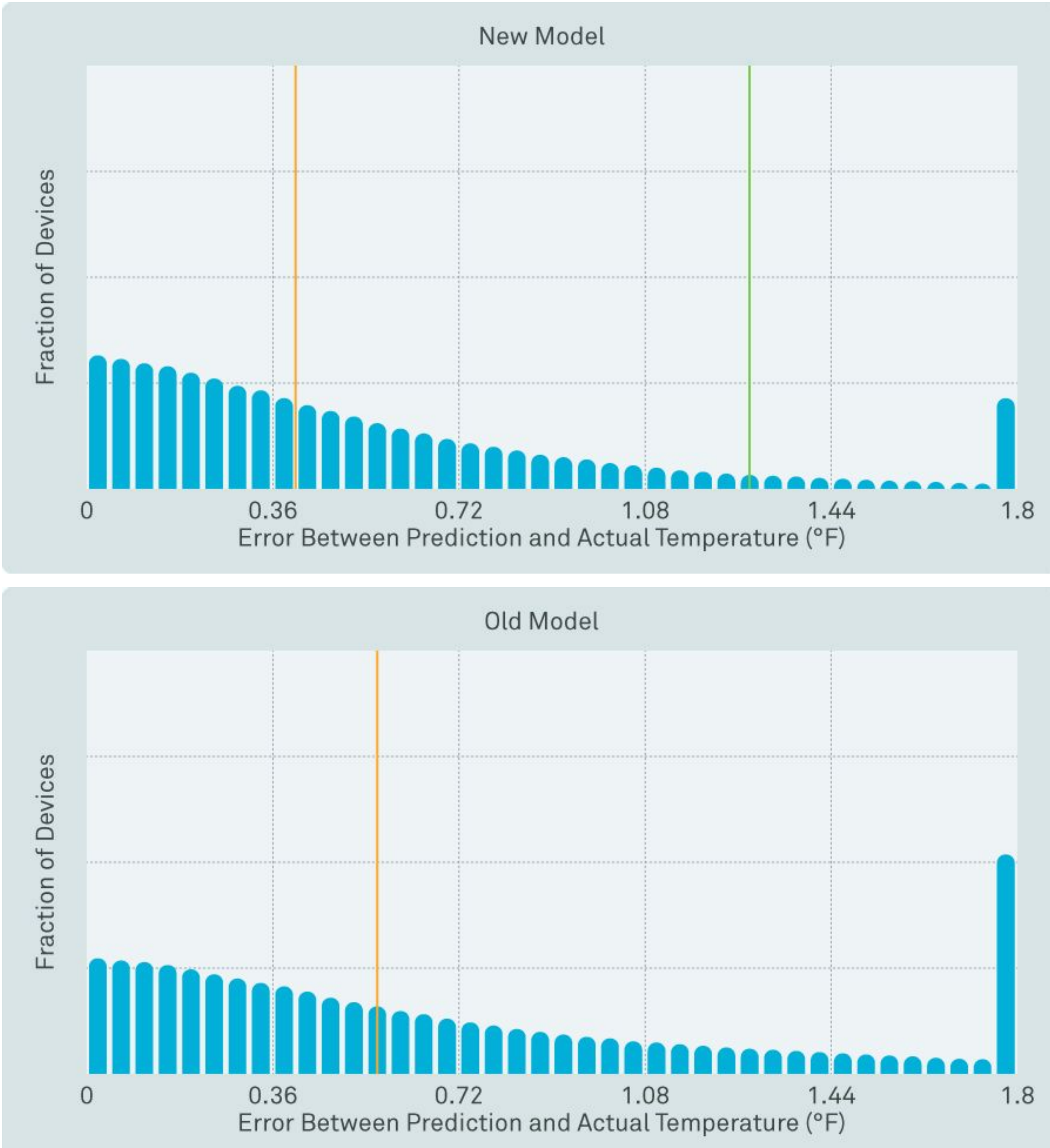

Figure III: The one-hour ahead indoor temperature prediction accuracy for the new model (top) versus the previous model (bottom) for a set of 1000 houses with heating systems during the winter. The orange line represents the median and the green line the 95th percentile value.

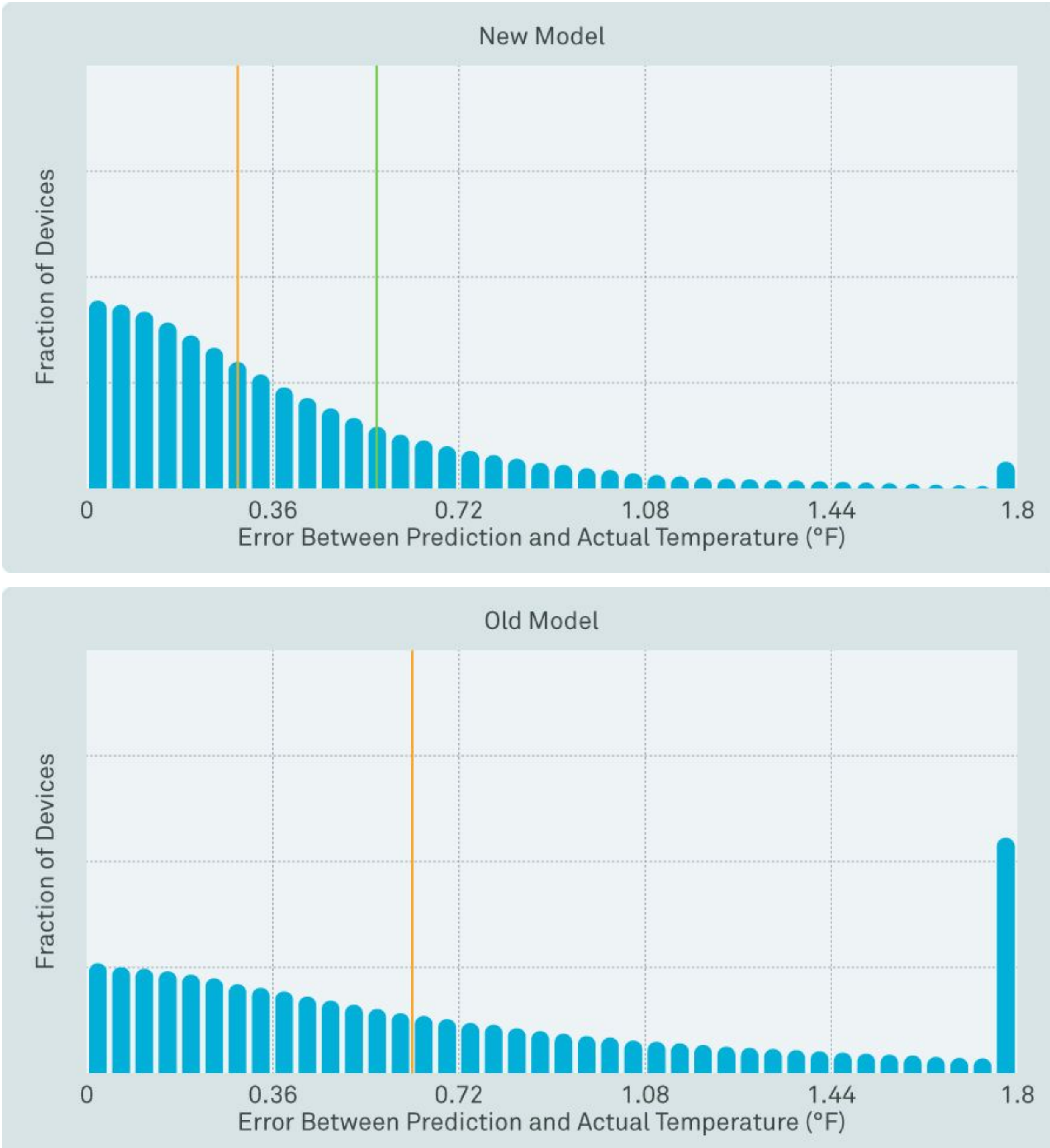

Figure IV: The one-hour ahead indoor temperature prediction accuracy for the new model (top) versus the previous model (bottom) for a set of 1000 houses with cooling systems during the summer. The orange line represents the median and the green line the 95th percentile value.

HVAC Control 2.0

What it is

HVAC Control 2.0 is a new feature available for all Nest Thermostat customers that changes the way the thermostat decides when and for how long to run the HVAC system. This new feature takes advantage of the home thermal model to customize the control of the HVAC system for each individual home, improving efficiency and comfort for users. These improvements allow us to achieve an even more tailored level of comfort, while achieving significant savings for multi-stage and heat pump systems when compared to traditional controllers.

Traditionally, thermostats control HVAC systems using a technique called bang-bang control [Sonneborn and Van Vleck (1965)]. Bang-bang control sets a maintenance band around the setpoint temperature, for example with 0.5 ℉ on either side of the setpoint temperature (Figure V). The system will run the A/C until the temperature hits the lower maintenance band, and then keep the A/C off until the temperature reaches the upper maintenance band. These behaviors are reversed for heating. This control technique ensures that the temperature is kept within a band around the desired temperature and that the HVAC system is not cycling on and off too frequently. For multi-stage systems, thermostats have some simple rules that determine when to use higher vs lower stages of HVAC based on the size of the setpoint change.

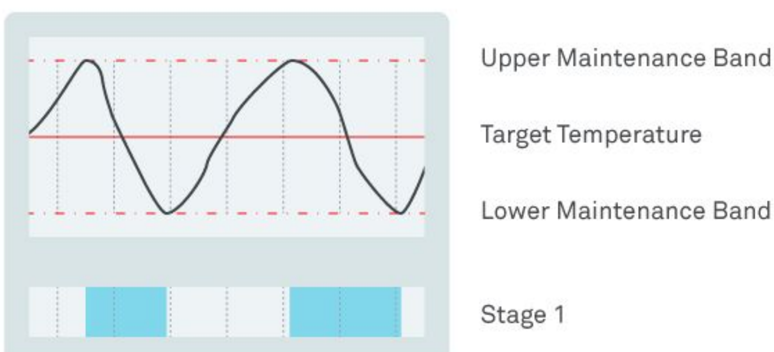

Figure V: An example of how the temperature in a home is controlled with a bang-bang control system. The AC is turned on with the indoor temperature hits the upper maintenance band and turned off when it hits the lower maintenance band.

Bang-bang control is a classical technique that has been around for decades. However, it has some drawbacks. The maintenance bands are applied to every house, regardless of whether that particular house is leaky or well insulated, or how efficient the HVAC system is. The bang-bang controller does not have any knowledge of upcoming schedule setpoints. For example, it may end up cooling right before an increase in the setpoint, or vice versa.

Multi-stage controllers choose between higher or lower HVAC stages using generic rules that are not specific to each house and HVAC system.

With the more accurate thermal model that Nest has developed, Nest can improve upon this classical control technique and personalize the control of the HVAC system to each house - accounting for the specific HVAC system, house, schedule, and weather. For example, if there is an upcoming setpoint increase, the controller can time the HVAC controls so that it is not cooling immediately before the setpoint increase. If there is warm weather outside, the controller can know to stop running the heater before reaching the upper maintenance band so that the house does not get over-heated. By customizing the control of the HVAC system to the particular house, this feature provides both saving and efficiency improvements over traditional control. HVAC Control 2.0 will be active on all systems except for True Radiant systems, for which Nest already uses alternate advanced control techniques.

How it works

HVAC Control 2.0 uses the thermal model to optimize the control of the HVAC system. It simulates many different ways that it could control the HVAC system. It must choose when to turn the system on, which stage of the system to turn on, how long to run that stage of the system, when to switch to a different stage, and when to turn the system off. It makes these choices while considering the current state of the home, the outdoor weather, and the upcoming schedule.

Figure VI shows a set of example control approaches that HVAC Control 2.0 might investigate. In this example, it is deciding how to heat the home from 71.5 ℉ to 76 ℉. It tries heating with all stage 1 heat, all stage 2 heat, and combining the two stages in different orders and lengths. For each approach, HVAC Control 2.0 uses the thermal model to predict how the indoor temperature will change given the HVAC state. It then gives each approach a score based on the HVAC runtime (weighted by how much power each stage uses to run) and the temperature in the house. The controller chooses the approach with the best score - the one with the best comfort and HVAC energy usage. The controller repeats this process every few minutes, whenever there is an updated temperature reading or scheduled setpoint.

Figure VI: Example control approaches that HVAC Control 2.0 evaluates in its search for the optimal control for a scenario where the setpoint has just been increased by over 4 ℉. It tries out (a) only stage 1 heat, (b) only stage 2 heat, (c) running stage 2 heat and then stage 1 heat, (d) running stage 1 heat and then stage 2 heat, and (e) running stage 2 heat, then stage 1 heat, and stopping early to avoid overshooting.

Results

Case Studies

HVAC Control 2.0 is able to provide customers with improvements in both comfort and efficiency over traditional control. Figure VII shows an example where HVAC Control 2.0 improves on efficiency over the typical control by planning for the upcoming weather. Knowing that a heat wave is coming in the new few hours, it does not heat the home as far past the setpoint temperature as usual, relying on the warmer weather to maintain the warm temperature for a long time. This approach both prevents the house from over-heating past the desired setpoint and saves the system from running more heating than necessary.

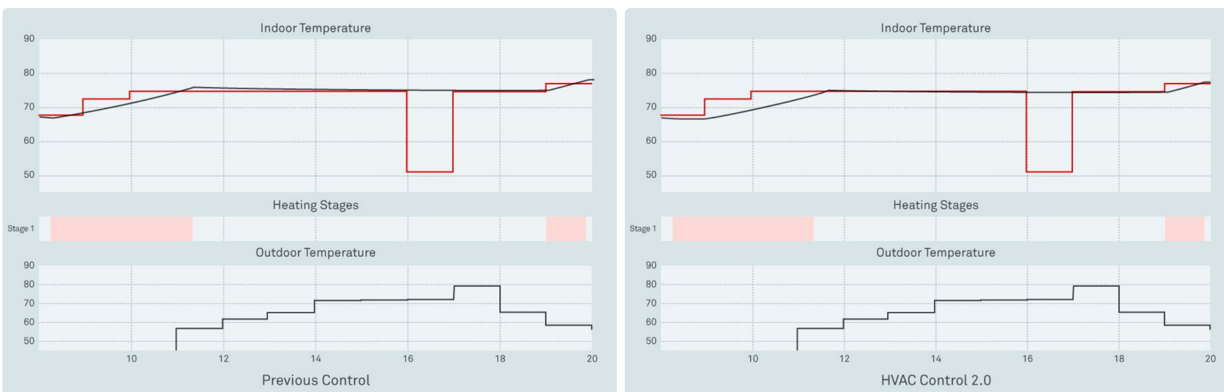

Figure VII: HVAC Control 2.0 vs traditional control in a scenario with an impending heat wave.

Another way that HVAC Control 2.0 provides better comfort and efficiency is through better control of multi-stage systems. Figure VIII shows an example of a system with a heat pump and auxiliary heat. Normally the auxiliary heat draws much more power (and is thus more expensive than the heat pump). HVAC Control 2.0 uses auxiliary heat to heat up past the setpoint temperature, and then runs the heat pump for a long period of time to maintain the temperature evenly. This approach both maintains a more even comfortable temperature and reduces the amount of costly auxiliary heating usage compared to the previous controller, which cycles the entire system off after running auxiliary heat.

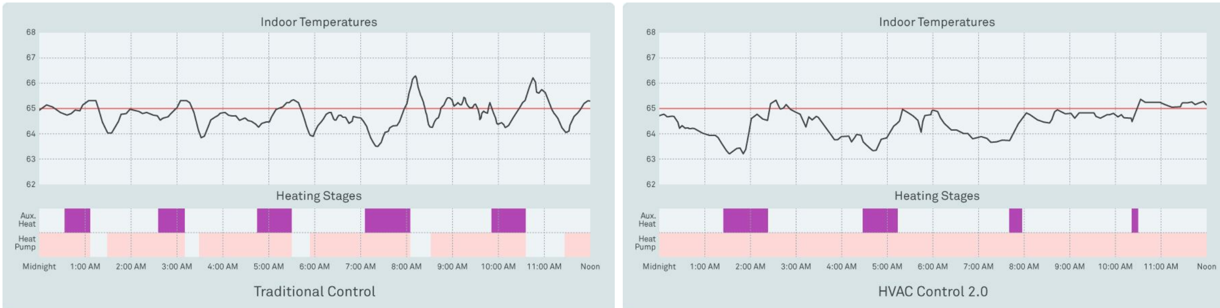

Figure VIII: Traditional control (left) and HVAC Control 2.0 (right) controlling a heat pump plus auxiliary heating system. On the left, the system turns off the heat after each aux cycle, with the temperature fluctuating more than with the controller on the right.

Predicted Results

Table 1 shows the average HVAC energy usage improvements predicted for different cooling and heating systems. To generate these results, we simulated control of hundreds of systems of each type (single stage heating, single stage cooling, multi-stage heating, multi-stage cooling, and heat pumps) using their actual weather and schedule from a random day in either January 2015 for heating systems or July 2014 for cooling systems. Simulations were run using various system types for each mode (e.g. forced air, electric, heat pump, single-stage, multi-stage, etc).

The savings anticipated by HVAC Control 2.0 vary by system type. The control of single-stage systems without Early-On enabled is already well-optimized and this update does not make a large impact on their energy efficiency. However, for multi-stage and heat pump systems, the savings may be significant. The simulations show that the average multi-stage heating system saves 3.8% HVAC energy usage, heat pump systems save an average of 6.5%, and multi-stage cooling systems save an average of 5.4% versus traditional bang bang control. These savings predictions account for the fact that higher stages draw more power than lower stages.

System Type	Multi-Stage Heating	Heat Pump Heating	Multi-Stage Cooling
Predicted Average HVAC Energy Savings	3.8%	6.5%	5.4%

Table 1: Predicted average HVAC energy savings for HVAC Control 2.0 when compared to Nest's previous control, separated by system type. These predictions are based on simulations of hundreds of devices of each system type.

In addition to savings, HVAC Control 2.0 can improve comfort, as simulations show that the controller maintains the indoor temperature 16.3% closer to the target temperature for heating and 20.4% closer for cooling than the previous controller. The comfort improvements are measured with one-sided-error. For example, for heating, the one-sided error measures how far and how frequently the ambient temperature in the home was below the setpoint temperature, but ignores when the ambient temperature was above the setpoint temperature. While the efficiency improvements mainly affect multi-stage systems, the comfort improvements are similar for both single-stage and multi-stage systems. The comfort improvements come from both reaching new setpoints faster as well as maintaining setpoints without as much temperature fluctuation.

Conclusion

Both the new home thermal model and HVAC Control 2.0 are exciting new improvements that bring cutting-edge technologies to the thermostat, improving comfort and efficiency for users. The new thermal model predicts future indoor temperatures with greater precision. The improved temperature prediction improves performance on features such as Time-to-Temperature, Early On, and Heat Pump Balance. HVAC Control 2.0 uses the new thermal model to choose control strategies for the HVAC system, providing a predicted average HVAC energy savings of 3.8% for multi-stage heating systems, 6.5% for heat pump systems, and 5.4% for multi-stage cooling systems relative to Nest's previous multi-stage control. These savings are achieved while maintaining the temperature up to 20% closer to the target temperature.

Simply put, the better Nest's model is at predicting your home's thermal conditions, the better able the Nest thermostat is at precisely hitting your desired comfort settings without expending extra energy to hit those targets. Both the new home thermal model and HVAC Control 2.0 personalize the modeling and control of the thermostat to individual homes and systems, improving comfort and efficiency for users.

References

- Sonneborn, L.; Van Vleck, F. (1965). "The Bang-Bang Principle for Linear Control Systems". *SIAM J. Control* **2**: 151–159