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# USING MOBILE DEVICE BATTERIES AS THERMOMETERS

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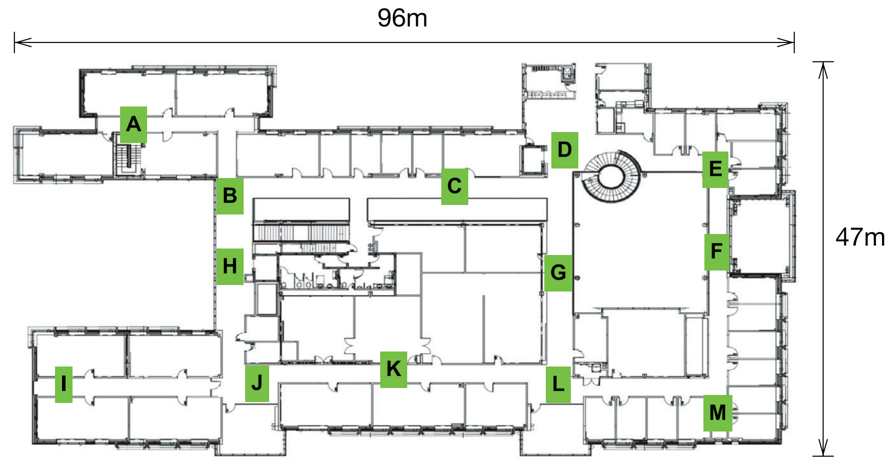
Sensing the ambient temperature is the key to many applications, such as smart homes/buildings/communities/cities [1, 2]. However, the ability to sense the ambient temperature pervasively is still deficient, causing various problems in people's daily lives, including but not limited to:

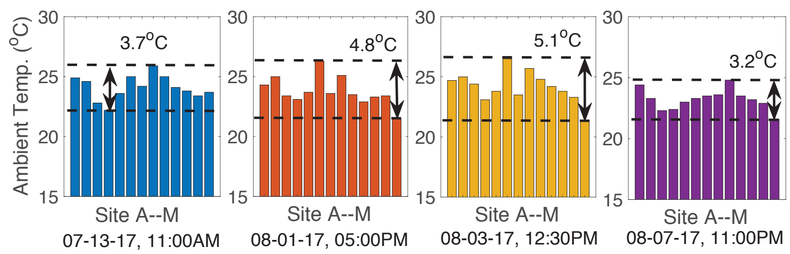
• **Degraded Indoor Thermal Comfort.** People spend more than 80% of their lives inside buildings, and thus the indoor thermal comfort is crucial to their wellness/productivity, especially in view of its spatial non-uniformity, as our empirical measurements show (see Figure 1). For example, about 8% of human mortality was shown to be due to non-optimum ambient temperature according to the data collected from 384 locations during 1985-2012 [3]. The West Midlands Public Health Observatory in the UK also acknowledged an increased mortality rate associated with an ambient temperature below 20°C. Such temperature-related mortality is expected to rise with the rapid aging of populations [4]. The real-time knowledge of a building's indoor temperature – especially in view of its spatial non-uniformness as shown in Figure 1 with our empirical measurements – is crucial to the occupants' thermal comfort [5]. However, such temperature information is not always available to the occupants, due to either the building's inability of temperature sensing or the occupants' inaccessibility to the collected temperature information.

• **Degraded Phone Operation.** The ambient temperature of mobile devices is crucial to their operation. A cold environment reduces the temperature of a device's battery, causing unexpected device shutoffs, as frequently reported by mobile users on both iOS and Android platforms. Figure 2 shows such an unexpected shutoff using an Xperia Z phone: during video streaming in a –15°C environment, the phone shut off even when it was shown to have 30% State-of-Charge (SoC). Such unexpected phone shutoffs are due to its inability to sense the environment temperature correctly, thus preventing the accurate prediction of the end-of-discharge battery conditions and displaying erroneous remaining SoC values. On the other hand, a hot environment aggravates the heating of a device's battery due to impeded heat transfer from the battery to the environment, accelerating battery degradation and risking device safety.

Temperature is usually sensed with thermometers, so letting people carry thermometers all the time is the best way of sensing their ambient temperature pervasively. Surprisingly, people have already been doing this: (i) they always carry battery-powered smartphones/watches, and (ii) there is always (at least) an active thermometer in such mobile device batteries to monitor the battery temperature. These facts render battery a promising means of sensing the ambient temperature, if we can estimate/decode the ambient temperature from the device's battery temperature, i.e., *exploiting mobile device batteries as thermometers.*




(a) The building floor map and 13 measurement sites.




(b) The temperature at each site differs by up to 5.1°C.

**FIGURE 1.** Non-uniform indoor temperature renders its sensing crucial to achieve the occupants' indoor thermal comfort.

## BATTERY AS THERMOMETERS!

To fill this need, we have designed a novel solution, called *Battery as Thermometers (BaT)*, for those who carry smartphones/watches [6]. BaT is inspired by our empirical finding that the mobile device battery's temperature is highly correlated with that of the device's ambient environment, as shown in Figure 3 with a Nexus 5X smartphone and a Galaxy Gear smartwatch, in which the device battery's temperature was collected from its fuel-gauge chip and the ambient temperature was collected with a temperature logger. BaT captures such a correlation to estimate the device's ambient

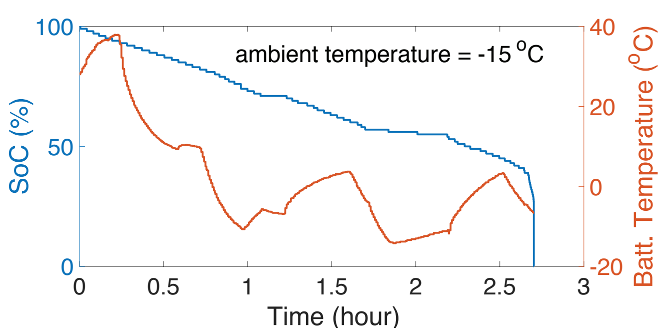



**FIGURE 2.** Lack of ambient temperature information causes unexpected device shutoffs in a cold environment.

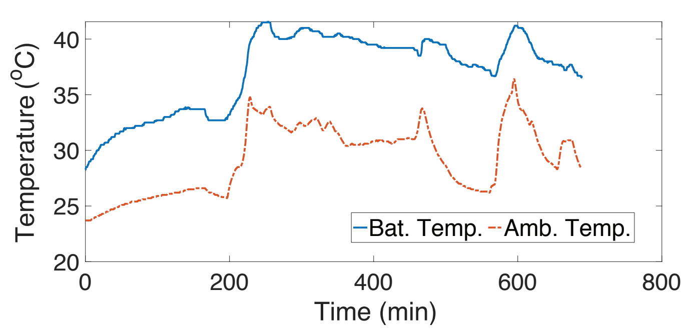



**FIGURE 3.** The temperature of a mobile device's battery is strongly correlated with that of its ambient environment.

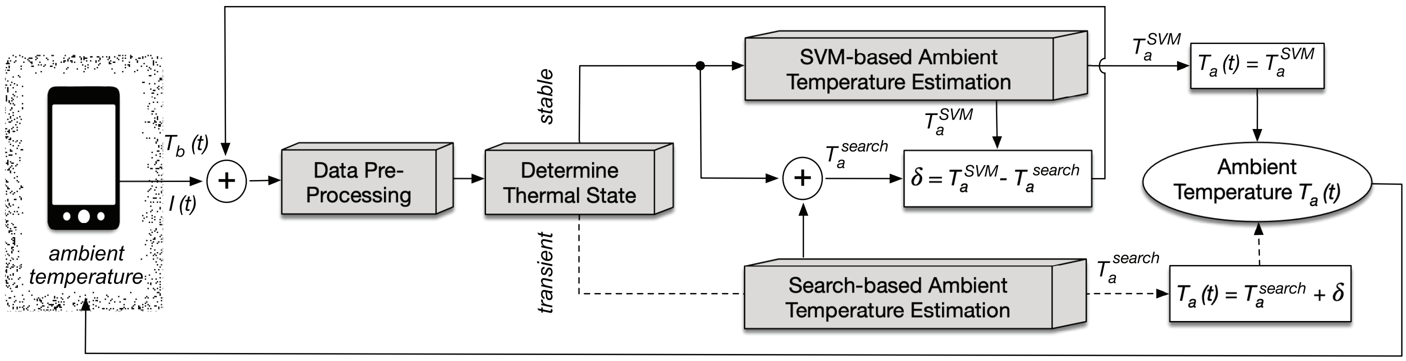



**FIGURE 4.** BaT estimates the device's ambient temperature according to a battery's real-time thermal state.

temperature, augmenting the ability to sense the physical world without requiring additional thermometers or taking up the limited space on mobile devices, i.e., sensing the temperature for free. The thus-sensed ambient temperature can then be made available to either devices or their users, depending on the specific need. As an example, we have validated the effectiveness of using BaT to incorporate the impact of ambient temperature in the estimation of battery SoC [7], mitigating the unexpected shutoffs of phones in a cold environment [8].

There are two key challenges in designing BaT. First, battery temperature is affected by its current, the ambient temperature, and the heating by other phone components, such as chips or screen. Such thermal interplays have traditionally been captured analytically in electrochemical and heat transfer models, which may need up to tens of describing parameters, depending on complexity/accuracy. Not all these parameters, however, are available on smartphones. To facilitate its deployability, BaT captures the battery's thermal behavior via integration of physical and data-driven modeling: abstracting the electrochemical models into generalized and empirically validated observations, and estimating the ambient temperature with such observations steered in a data-driven way. Also, battery could be in either transient or stable thermal state, according to which its correlation with a device's ambient temperature needs to be decoded differently. This is particularly critical because a mobile devices' dynamic current, together with mobile users' frequent movements and thus change of ambient, cause the device's battery to make frequent state transitions. BaT identifies the battery's thermal states based on its recent temperature/current and applies different (but closely-coupled via a control loop) techniques to estimate the ambient temperature. Figure 4 provides an overview of BaT.

**TABLE 1.** Classification of the 48 apps from Google Play

| Type | Description | # of Apps |
|---|---|---|
| I | Estimates body temperature based on heartbeats | 6 |
| II | Returns the outdoor temperature of users' current location | 11 |
| III | Requires additional hardware/gears | 9 |
| IV | Returns the reading of a phone's certain thermometer | 9 |
| V | Estimates based on a phone's certain thermometer | 13 |

BaT has the following advantages over other (potential) solutions of pervasive temperature sensing:

• **BaT vs. Hardware Thermometers.** An ideal way of sensing temperature pervasively is to have everyone carry a thermometer all the time, as they carry a mobile phone. Inspired by this fact, Android provides the function of acquiring the device's ambient temperature, but such a function is applicable only when device manufactures have built hardware-based thermometers into their devices, as with Samsung's Galaxy S4 and Note 3 smartphones. Clearly, such built-in thermometers increase the cost of the device and take up the limited space within the device. Moreover, our examination of Galaxy Note 3's ambient thermometer driver uncovered that it just calibrates the raw thermo readings linearly with fixed coefficients, making the thus-estimated ambient temperature unreliable.[1] Instead of requiring additional hardware thermometers, BaT, as a (semi-)software-defined thermometer, enables mobile devices to sense, when needed, their ambient temperature using the thermometers built in their batteries, which are pervasively available on all commodity mobile devices.

• **BaT vs. Software-Defined Thermometers.** To the best of our knowledge, little has been done to explore the software-defined thermometers, i.e., extracting/estimating ambient temperature from device batteries, and the closest to BaT are [9–12]. Crowd-sourcing is used in [9] to estimate the air temperature in highly populated areas. The design therein, however, only estimates daily average air temperature with coarse spatial granularity (e.g., of city level) and accuracy (e.g., up to 20% error [13]), thus making it inaccurate and also untimely. Chau [10] developed a method to estimate air temperature using smartphone batteries, which is, however, applicable only to batteries that are in a stable thermal state.

[1] Samsung has removed these hardware thermometers in its later models.

The temperature of the mobile device battery is used to estimate/predict the device's surface temperature in [11], achieving less than 2°C error; BaT extends significantly the exploration to estimate the device's ambient temperature. Breda et al. [12] estimated the ambient temperature by considering four operation states of phone/battery, which BaT simplifies to two states (i.e., stable and transient thermal states of the battery) by identifying the dominating factors in describing the thermal coupling among phone, battery, and ambient.

• **BaT vs. Commercial Apps.** There are many apps called "thermometer" or similar names in Google Play App Store. To study these apps, we installed the first 48 apps found by searching Google Play with the key word "thermometer" and summarized their functionalities in Table 1: only 13 of them (i.e., Type-V) can potentially be exploited to estimate a device's ambient temperature. To further examine the accuracy of these 13 apps (indexed as #1-13), we ran them with varying settings as listed in Table 2. Specifically, we use an app BatteryDrainer to regulate the phone's operation (and hence control their discharge rate) and a thermal chamber to control the the phone's ambient temperature. The phones are placed in the chamber for 30 to 60 minutes, and then the estimated ambient temperature with these apps is recorded. These measurements show (i) 6 of these apps (i.e., #8-13) always return the same estimations, and thus they are of the same estimation algorithm; (ii) these apps suffer from up to 15°C error in estimating the devices' ambient temperature, especially when the discharge current is large. Our experiments show BaT to sense the ambient temperature with errors in [-0.9, 1.4]°C and an average of 0.64°C, which is much more accurate than these apps and is comparable to the ±2°F (or ±1.1°C) accuracy of the off-the-shelf Acurite Weather Station.

**TABLE 2.** Error (in absolute value) of the 13 Type-V apps in estimating phones' ambient temperature

| Experimental Settings | | | Error of Apps (°C) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Phone | Ambient Temp. | DChg Current | #1 | #2 | #3 | #4 | #5 | #6 | #7 | #8-13 |
| Nexus 5X | 22°C | 256mA | 1.1 | 5.6 | 6.1 | 2.1 | 4.1 | 5.1 | 7.4 | 2.6 |
| Nexus 5X | 23°C | 836mA | 10.7 | 9.5 | 9.7 | 7.7 | 5.7 | 10.7 | 11.7 | 6.7 |
| Nexus 5X | 24°C | 1,220mA | 15.1 | 11.0 | 14.1 | 12.1 | 4.1 | 15.1 | 15.4 | 10.9 |
| Nexus 6P | 22°C | 329mA | 1.0 | 1.8 | 3.0 | 1.0 | 3.0 | 2.0 | 3.0 | 1.6 |
| Nexus 6P | 23°C | 600mA | 9.7 | 7.7 | 8.7 | 6.7 | 2.7 | 9.7 | 10.2 | 5.4 |
| Nexus 6P | 24°C | 1,550mA | 12.8 | 8.7 | 11.8 | 8.8 | 10.8 | 11.8 | 12.4 | 7.5 |

## CONCLUSIONS

We have presented BaT, which senses mobile devices' operating ambient temperature using their batteries, expanding the ability to sense the physical world pervasively without requiring additional thermometers. BaT is inspired by (i) the fact that people always carry their mobile devices, and (ii) our empirical finding that the temperature of a device's battery correlates highly with that of a device's ambient temperature. BaT has the potential for steering many applications, such as facilitating environment-aware battery management for mobile devices or helping users find their comfort areas in a building. ■

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