EVALUATING ENERGY-EFFICIENCY USING THERMAL IMAGING

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MOTIVATION

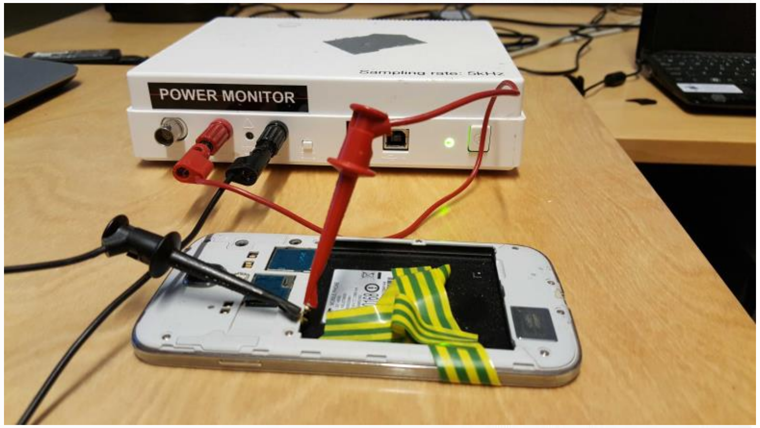
How to evaluate energy footprint of apps on emerging IoT / wearable / mobile devices?

- No direct access to power source
- Difficult to separate overall power draw vs power consumed by software

CURRENT SOLUTIONS

Hardware power monitors

- Highly accurate for instantaneous power consumption
- Require connection between power source and device (detachable battery / power source)
- Bulky and limited to fixed contexts



Power profiling

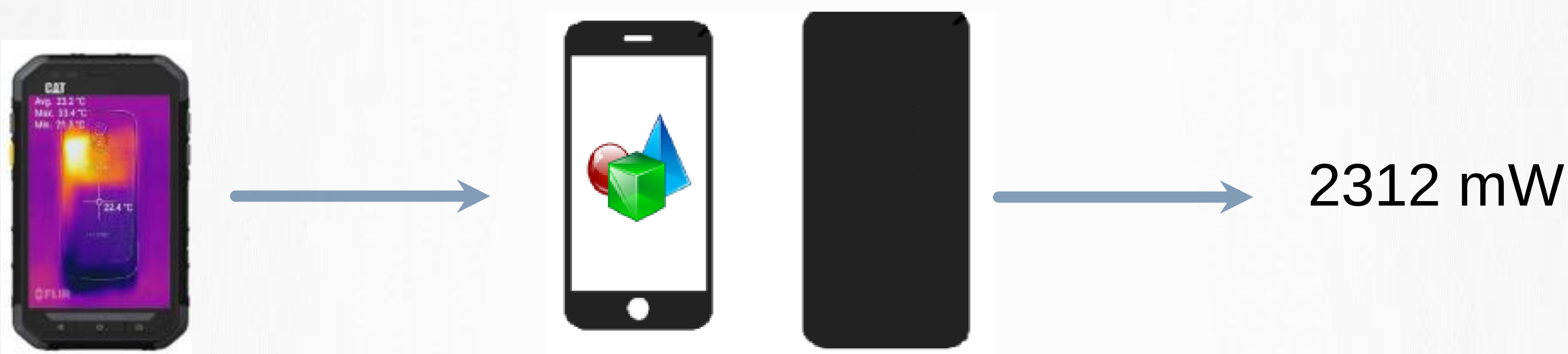
- Mathematical models of energy, can be constructed through software or hardware sampling
- Vulnerable to biases (testbed, sampling method, measurement context, …)
- Limited generality and better at relative than absolute estimates

THERMAL IMAGING

- Off-the-shelf devices with thermal cameras increasingly available
  - Smartphones: Caterpillar S60 and S61
  - Attachable: FLIR One range of thermal cameras
- Relies on *forward looking infrared (FLIR)*
  - Measures thermal radiation, not temperature
  - Off-the-shelf devices *uncooled* making them sensitive to heating of the device

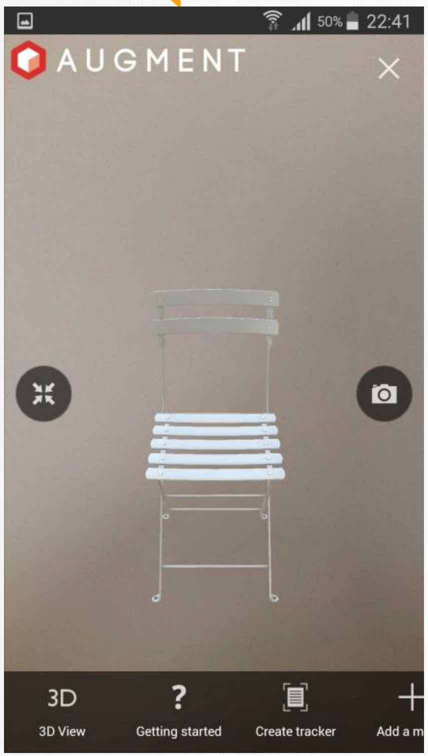
THERMAL ENERGY-EFFICIENCY

- General idea simple: take thermal image of device running an app and convert that into an energy estimate
- Conversion from thermal energy to power governed by Stefan-Boltzmann law: $P = \varepsilon\sigma AT^4$
  - A = surface area
  - ε = emissivity of material
  - σ = Bolzmann constant

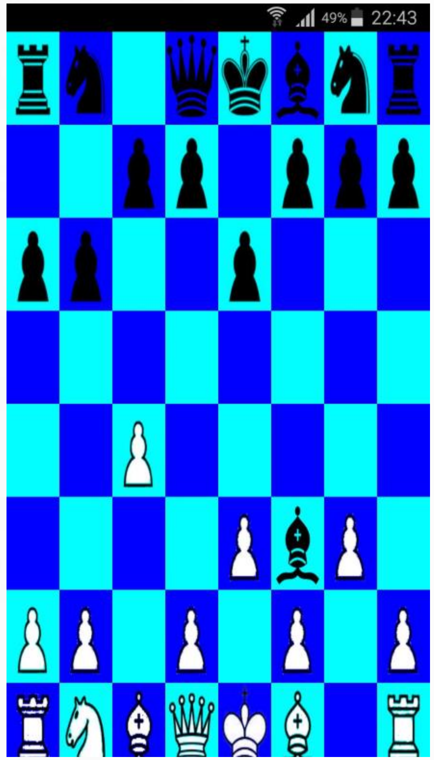


SOUNDS HOT,
DOES IT ACTUALLY WORK?

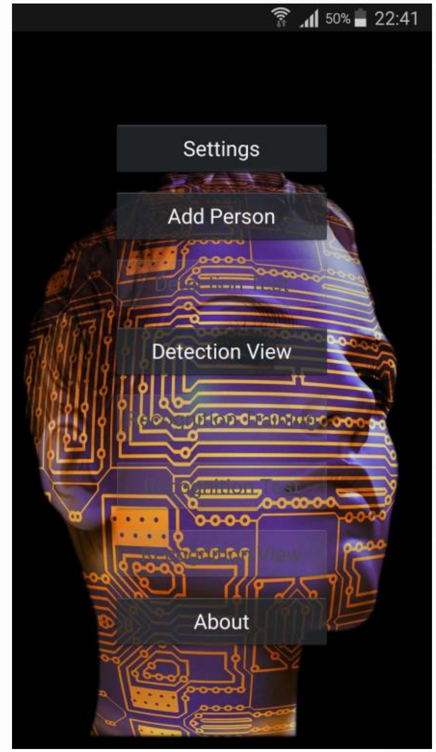
EXPERIMENTAL SETUP



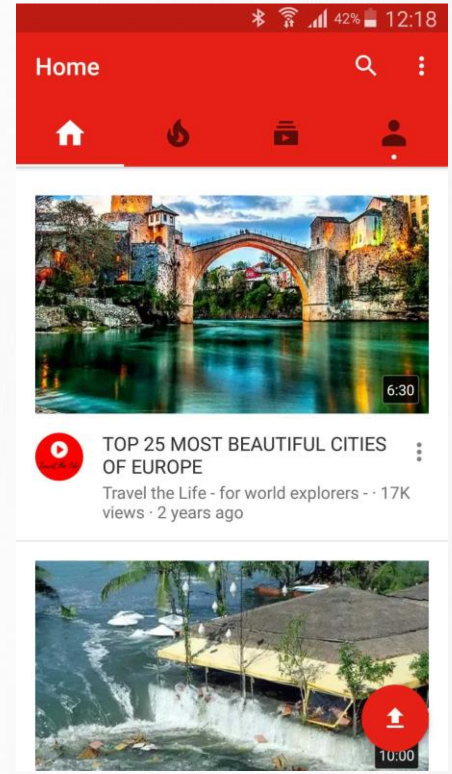
Augment: augmented reality application that allows manipulating and viewing virtual objects



Chess: puzzle game that allows playing against a computer opponent (minimax algorithm)



Face: application that allows device to identify a person based on facial recognition



YouTube: used for separate discharge experiments

EXPERIMENTAL SETUP

Room
22-24 Celsius degrees

Samsung Galaxy S5 Nexus (i9250)

Fridge for cooling down devices between experiments

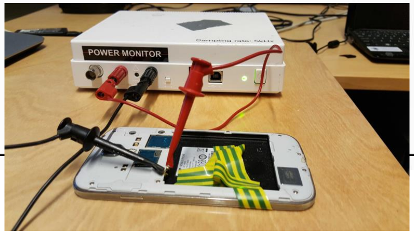
CAT Phone

3) Take thermal picture

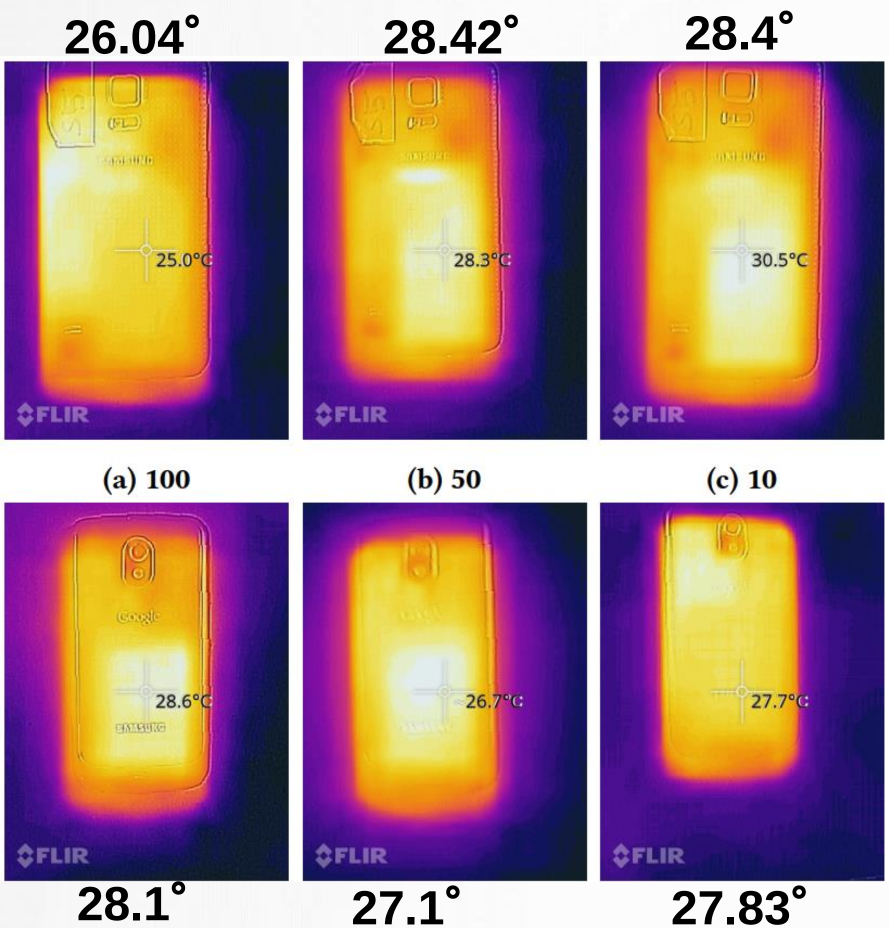
1) Running app

2) Flip to Backside

Monsoon as baseline



RESULTS: FEASIBILITY ANALYSIS



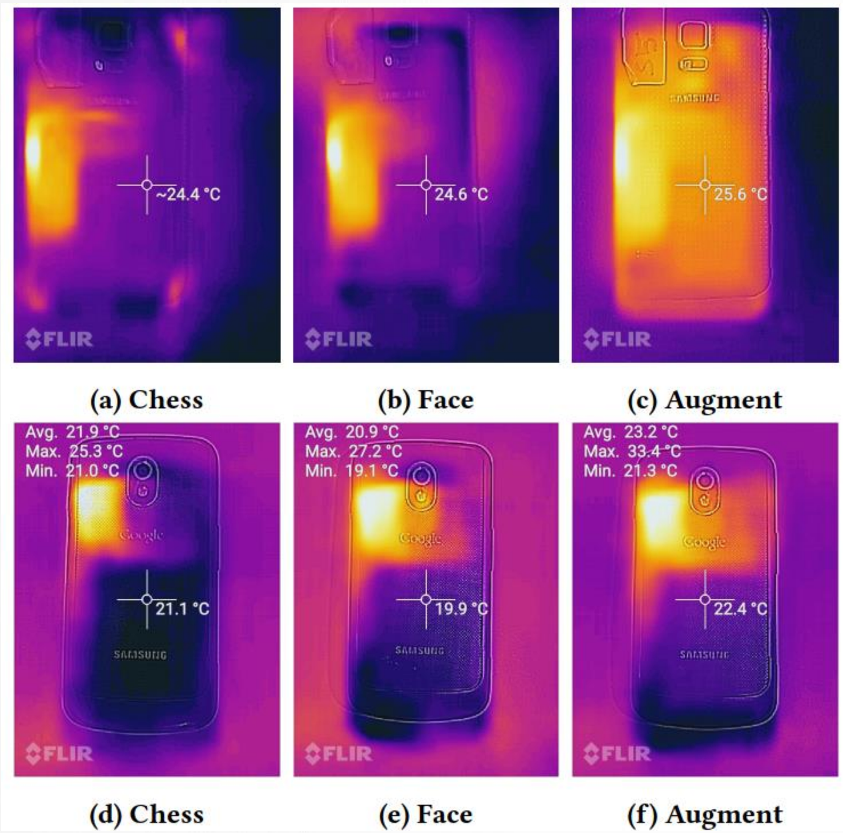
Experiment Setup:
Discharge experiment where constant charge (YouTube) applied until device empty

Results: avg. temperature difference 0.77° across all battery levels

➔ Thermal footprint is sufficiently stable over time when load is constant

RESULTS: ENERGY FOOTPRINT

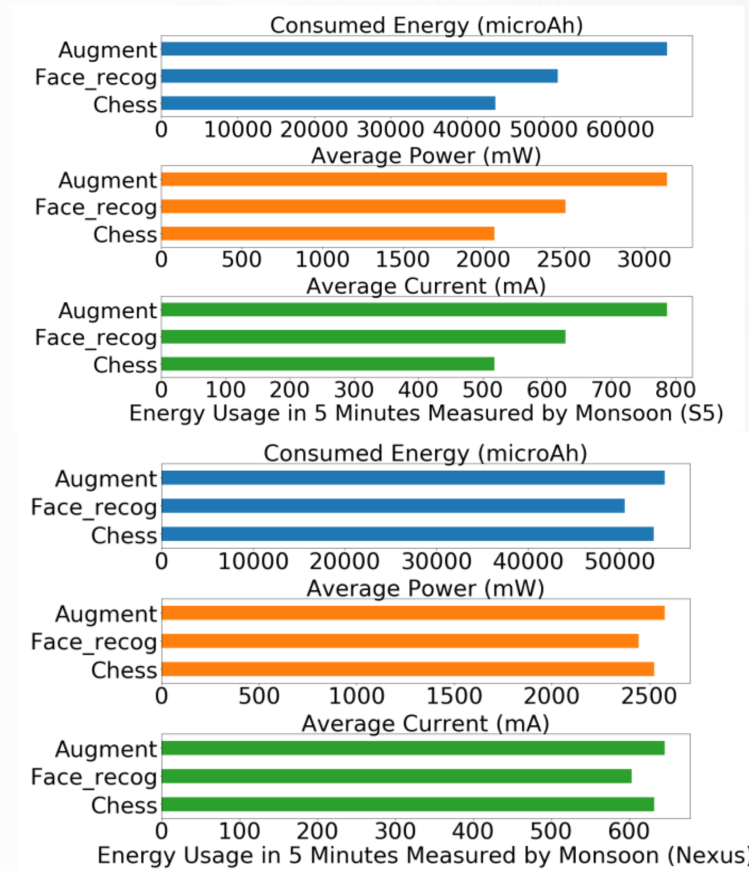
Δ1.25° Δ 1.41° Δ 1.47°



(a) Chess (b) Face (c) Augment

(d) Chess (e) Face (f) Augment

Δ1.82° Δ 1.26° Δ 2.07°



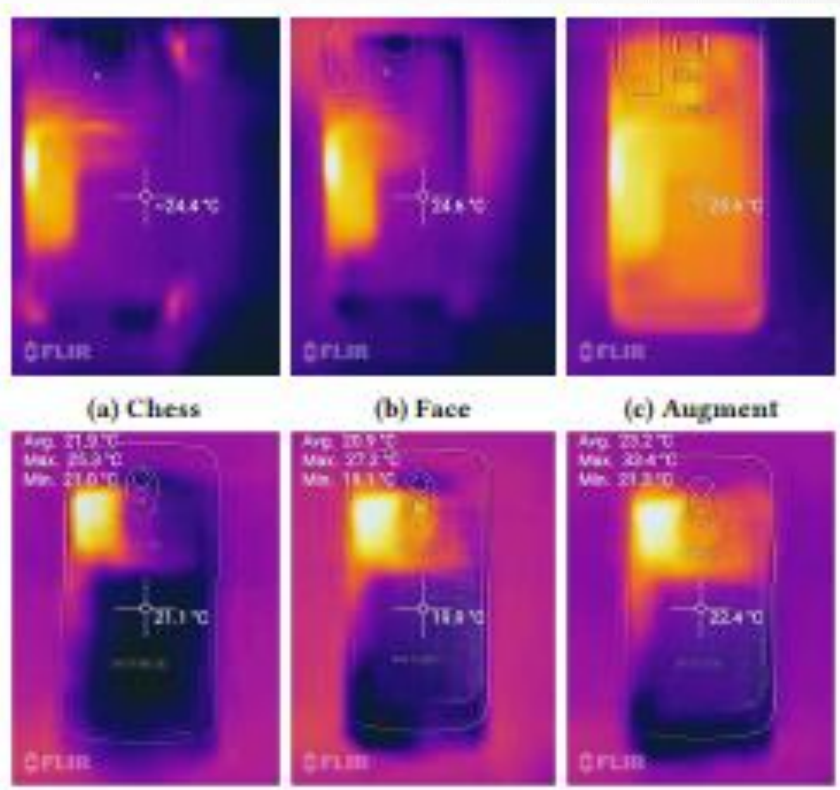
CHALLENGES: ABSOLUTE ESTIMATES

	Augment	Face	Chess
Monsoon S5	3138.93	2509.74	2067.50
Thermal S5	15544.51	14654.03	14917.53

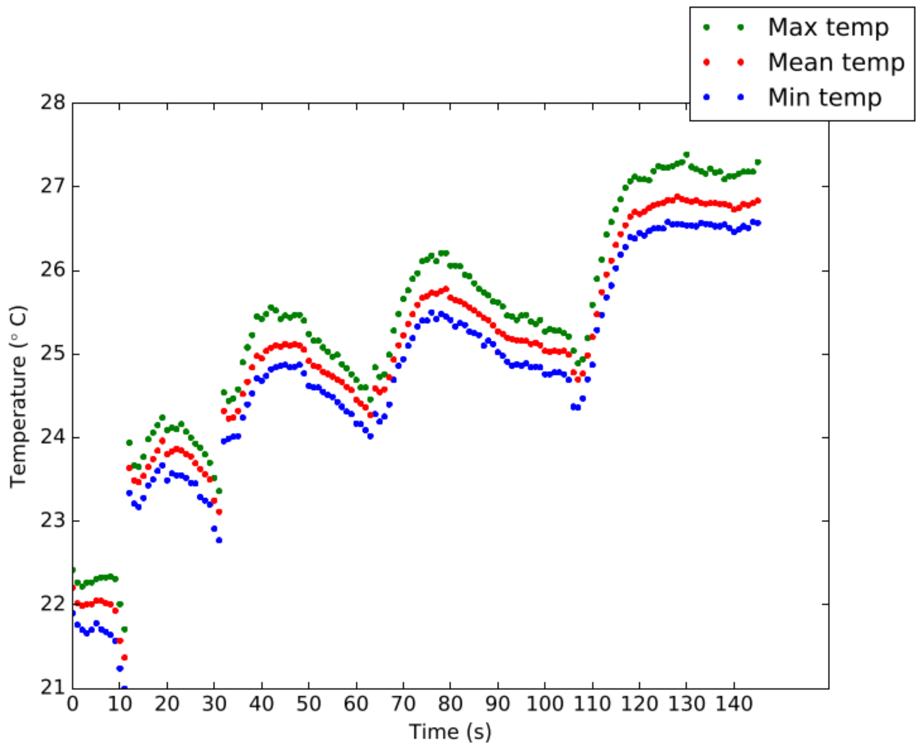
- Absolute estimates sensitive to accuracy of emissivity and surface area estimates
- Relative estimates for *same* device insensitive against inaccuracies in these estimates

CHALLENGES: MEASUREMENT AREA

- Thermal footprint varies across apps depending on which components they utilize
- Accurate thermal estimation requires region-based thermal estimates that take into account different system components



CHALLENGES: CALIBRATION



- In *continuous* monitoring, accuracy of thermal imaging suffers due to heat seeping to the thermal sensor
- Errors can be mitigated through calibration
- Our experiments used individual images to avoid issues from heating of thermal sensor

"***Hot or Not? Robust and Accurate Continuous Thermal Imaging on FLIR cameras***", T. Malmivirta, J. Hamberg, E. Lagerspetz, X. Li, E. Peltonen, H. Flores, P. Nurmi, PerCom 2019

DISCUSSION

Challenges

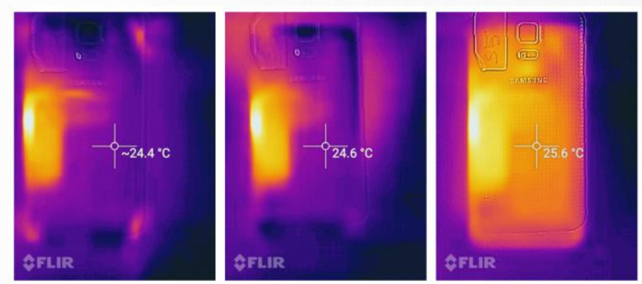
- Higher accuracy requires potentially images from multiple different angles / viewpoints (e.g., front screen vs. backside)
- Thermal output depends on *surface emissivity* of material that is being monitored
- Heat conduction from internal and external sources affect thermal energy transfer

Advantages

- Independent of power source and charging/discharging state of device being monitored
- Applicable without access to battery / power source
- Can operate in different contexts

SUMMARY

- Introduced a novel approach for estimating *relative* energy footprint of IoT devices using thermal imaging
- Demonstrated feasibility of our idea through benchmark experiments
  - Thermal footprint stable for constant operating load
  - Thermal footprint differs across apps with different intensity levels
  - Relative differences in footprint match with power monitor results



Thank you!

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