Data Quality Objectives for Air Sensors in Human Exposure and Health Research Studies: PM_{10}, NO_2, SO_2 and CO

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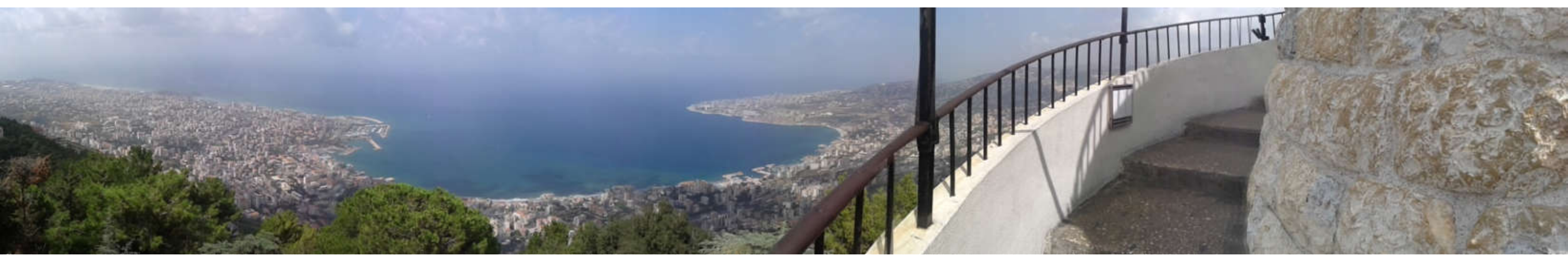
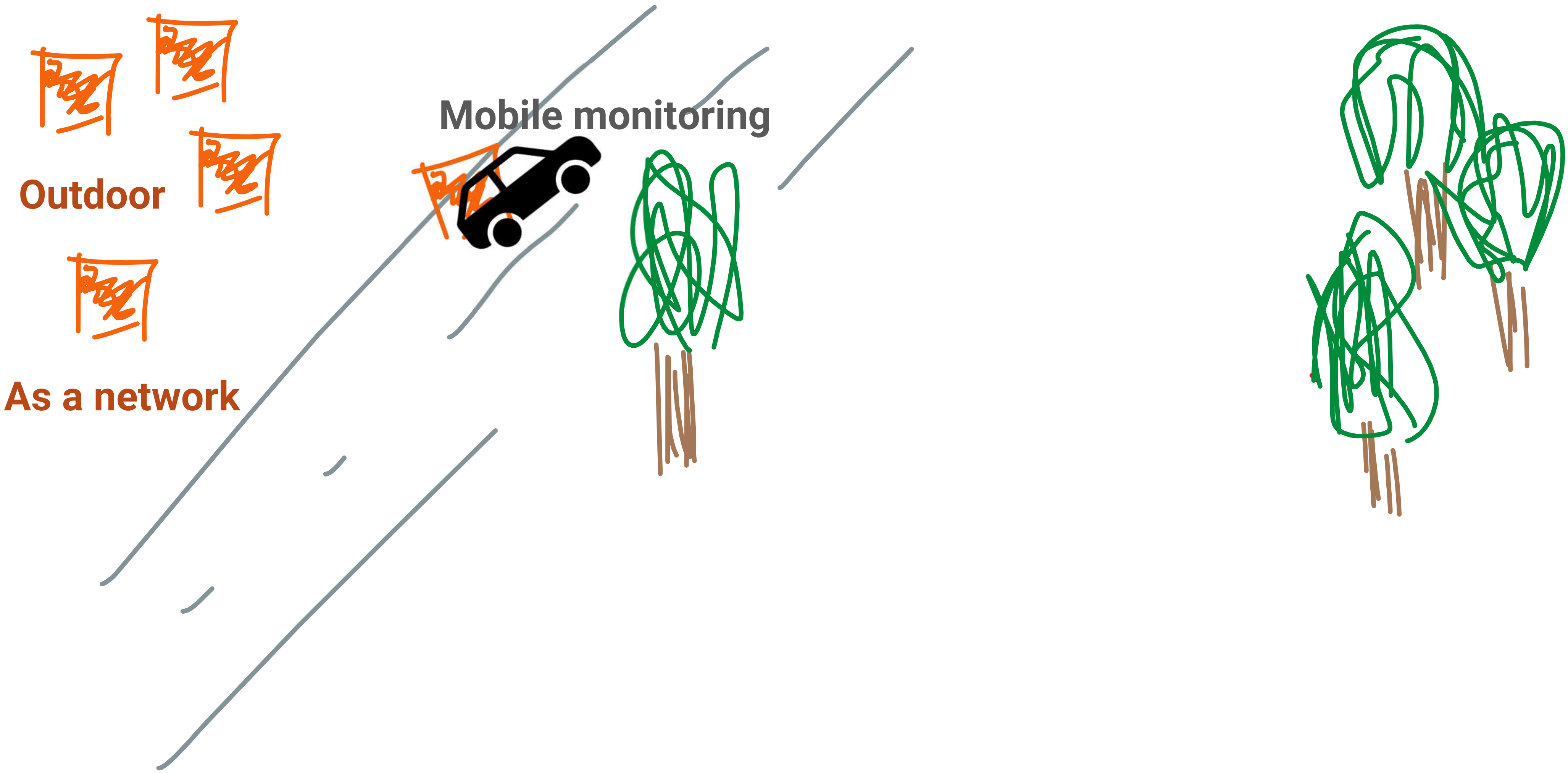
EPA Air Sensors Conference II, July 2019



Outline

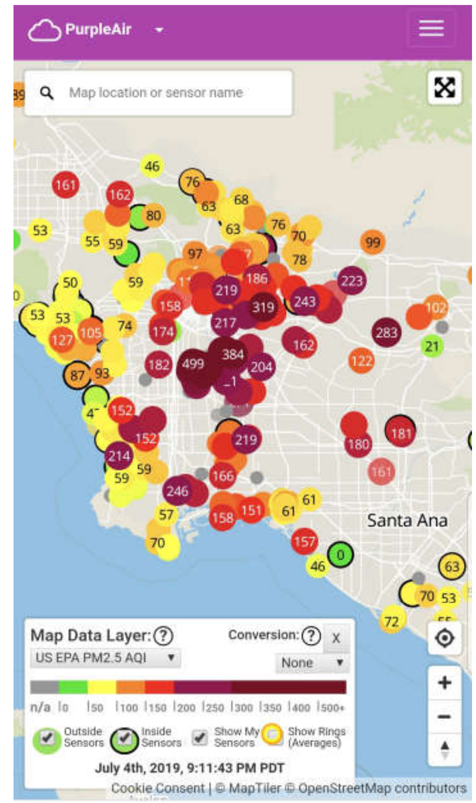
- Major exposure and health research applications for low-cost air quality sensors
- Universal calibration challenges
- Current data on PM_{10}, NO_2, SO_2, CO low-cost sensors
- Desired performance targets for exposure and health research
- Pollutant-specific considerations by deployment type
- Recommendations for sensor manufacturers/sensor community
- Need for acute exposure and health risk research

Outdoor


Mobile monitoring
Outdoor
As a network

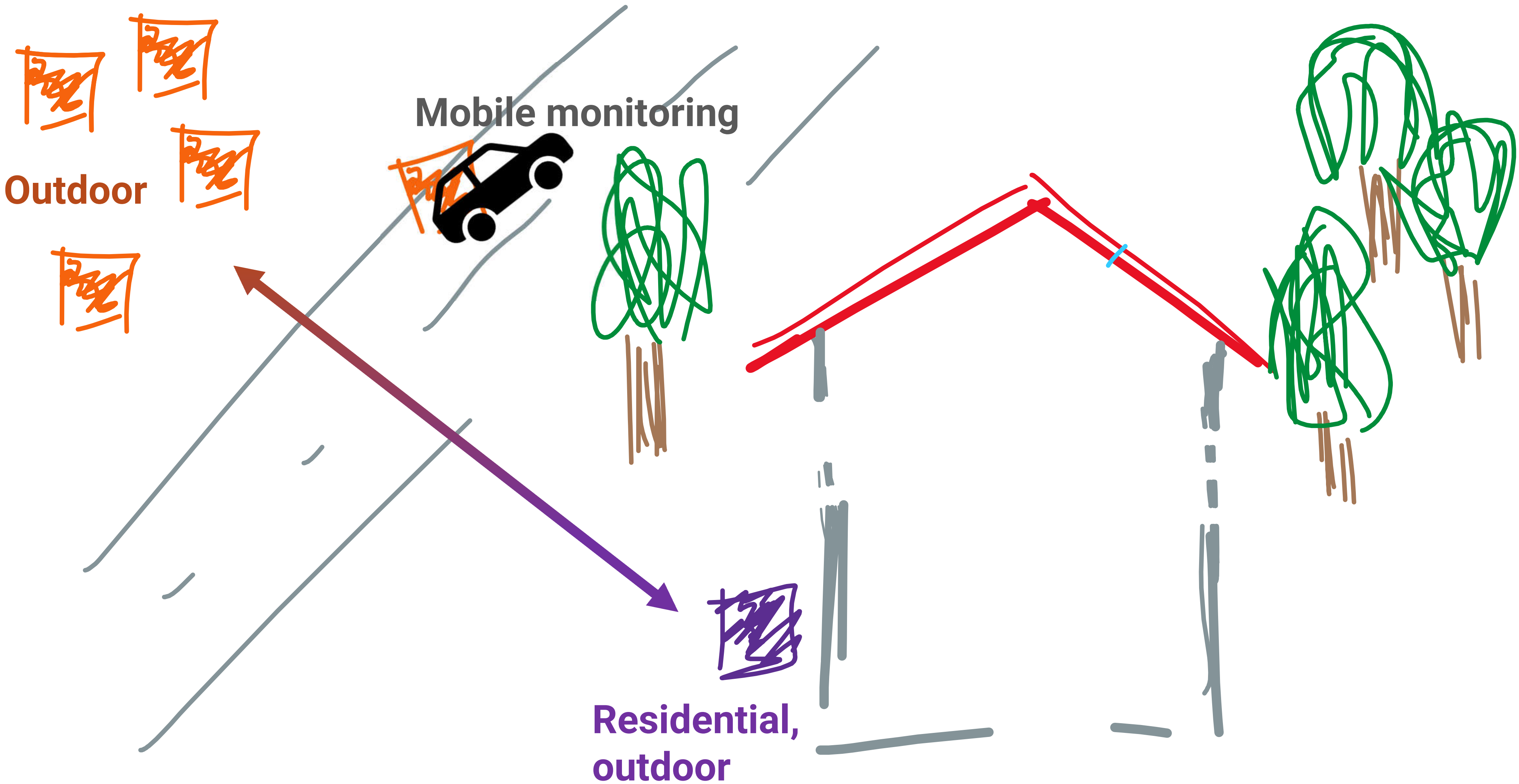
Spatial scales for outdoor monitoring

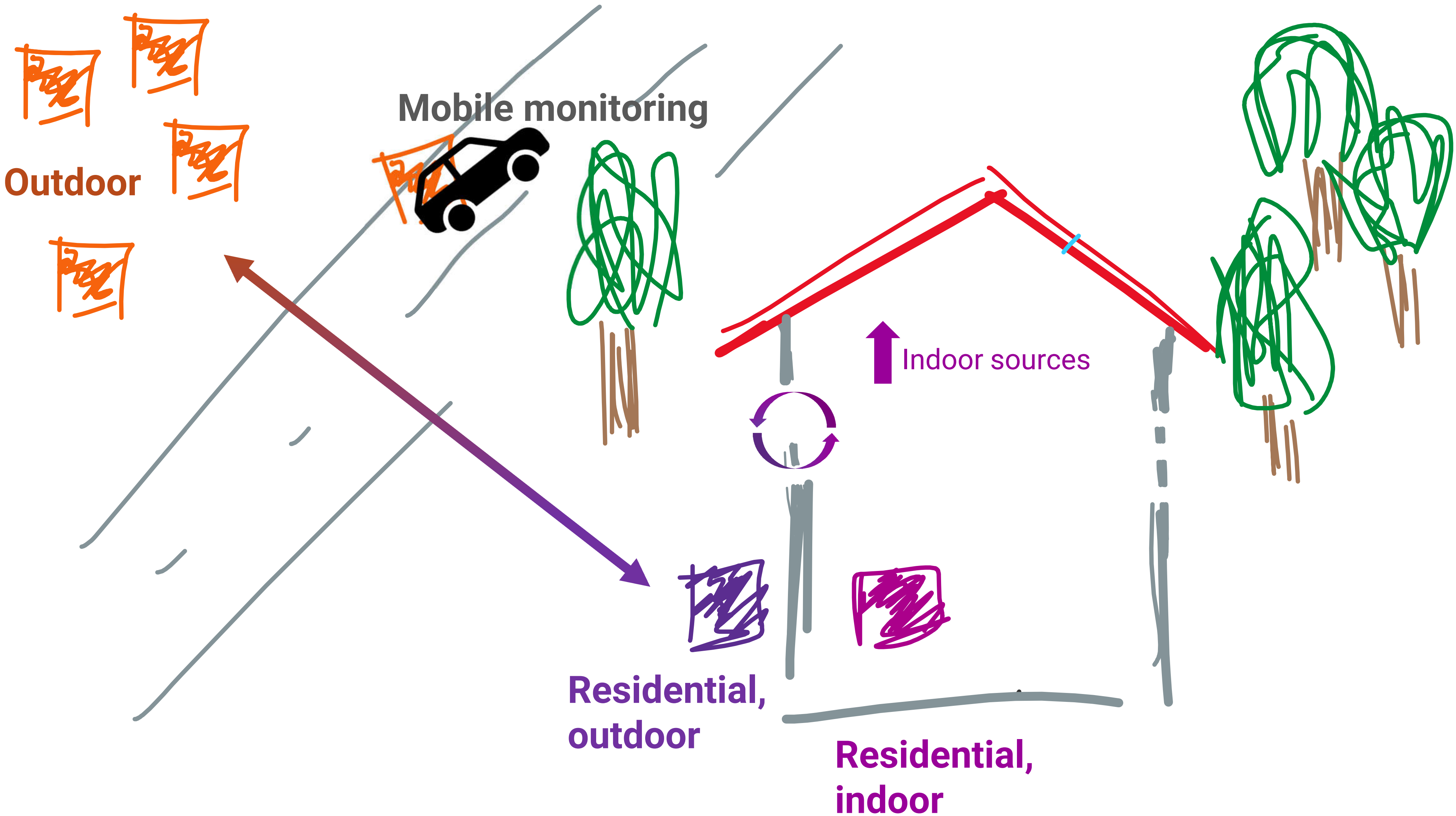
100m Micro | *500m* Middle | *4,000m* Neighborhood | *50,000m* Urban | *100,000m* Regional | National and global

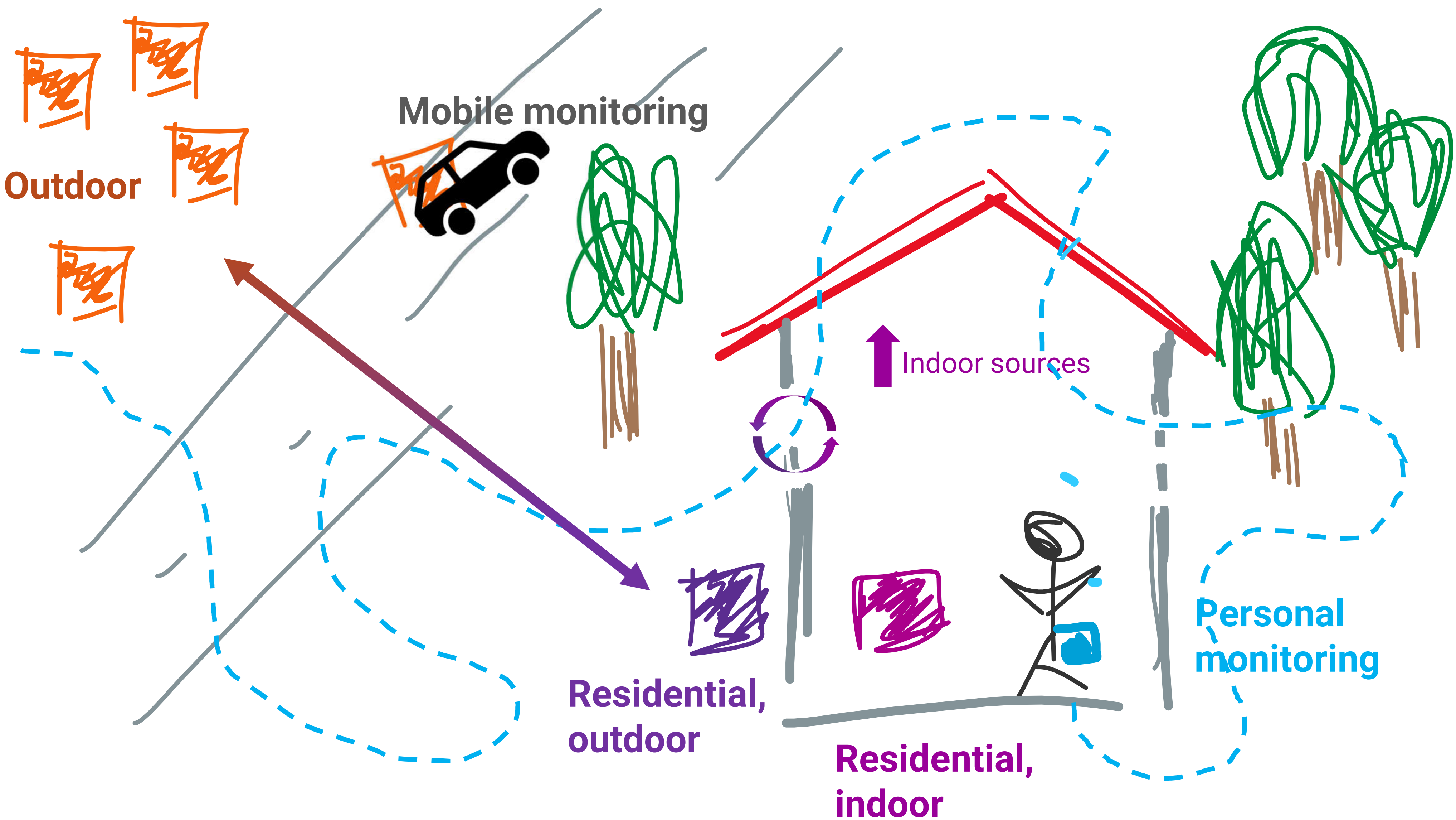


Los Angeles, CA area, 4th of July fireworks, 2019
Purple Air Map, courtesy of Dr. Mariam Girguis

40 CFR Part 58, Ambient air quality surveillance, Appendix D to Part 58—Network Design Criteria for Ambient Air Quality Monitoring, from: https://www.ecfr.gov/cgi-bin/text-idx?SID=c7fae1149eb6eeaa96ea607c0b871570&mc=true&node=ap40.6.58.0000_0nbspnbspnbsp.d&rgn=div9


Mobile monitoring
Outdoor
Residential,
outdoor


Mobile monitoring
Outdoor
Indoor sources
Residential, outdoor
Residential, indoor


Outdoor
Mobile monitoring
Indoor sources
Residential, outdoor
Residential, indoor
Personal monitoring

Major research applications

Ambient/outdoor monitoring

- Increasingly powerful as networks
- Collocated to FEM/FRM for calibration purposes (min 1m-4m spacing for flow rates <200lpm)
    - Important to understand intended spatial scale of EPA/local monitor!
    - Important to differentiate real spatial variability from “colocation”
- Geographically weighted regression, machine learning, other techniques to derive spatiotemporal surfaces that capture and integrate all spatial scales listed above, integrated with ground monitors and satellite data
- Outdoor mobile monitoring on cars, drones, etc..

Residential (outdoor/indoor) and personal monitoring

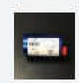
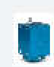
- *Paired* residential outdoor and indoor monitoring
    - Spatial variability of outdoor pollution, infiltration of outdoor pollution indoors, indoor sources and concentrations, decreased measurement error compared to central sites, no mobility, stationary calibration possible
- Personal monitoring
    - Gold standard, accounts for mobility, complex calibration requirements, movement across microenvironments and quick RH/temp changes, higher burden for wear compliance, higher requirements on researchers/developers for user engagement (data visualizations etc..), stationary calibration useful but might not be sufficient

Universal calibration challenges

- Geographically relevant calibration (in terms of aerosol size distribution, composition, meteorological conditions etc..)
- Deployment relevant calibration (stationary outdoor, stationary indoor, or mobile/personal) – need to imitate actual deployment conditions during calibration for relevance
  - Especially challenging for personal deployments
- More demanding, more frequent, and faster turnaround calibration needs → *need more scalable, "smart" calibration solutions, combination of automatic, user end, on sensor manufacturer end?*

Current AQ-Spec Evaluations
PM_{10}, NO_2, SO_2, CO sensors

Sensor Image	Make (Model)	Est. Cost (USD)	Pollutant(s)	*Field R^2	*Lab R^2	Summary Report
	Alphasense (OPC-N2)	$310	PM_{10}	0.45 to 0.57	0.99	PDF (1,291 KB)
	PurpleAir (PA-I)	$150	PM_{10}	0.32 to 0.44	0.97	PDF (1,072 KB)
	PurpleAir (PA-II)	$200	PM_{10}	0.66 to 0.70	0.95	PDF (1,328 KB)

Sensor Image	Make (Model)	Est. Cost(USD)	Type	Meas.	*Field R^2	*Lab R^2	Summary Report
	Aeroqual (AQY) Ver. 0.5	$3,000	Electrochem	NO_2	0.77	0.98	PDF (1,158 KB)
	CairPol Cairsens (CO)	$1,243	Electrochem	CO	0.94		
	CairPol Cairsens (NO_2)	$1,198					
	UNITEC (SENS-IT)	$2,200	Metal Oxide	CO	0.33 to 0.43	0.99	PDF (1,283 KB)
				NO_2	0.60 to 0.65		

http://www.aqmd.gov/aq-spec/evaluations/summary-pm

http://www.aqmd.gov/aq-spec/evaluations/summary-gas

Desired DQOs for research applications

- As close to FEM as possible on *hourly* basis
- Exposure and health studies conducted to inform NAAQS
  - Demonstrate or quantify health risks at or below current NAAQS
  - Investigate threshold effects at very low concentrations
  - Need to legally conform to FEM/FRM standards for Integrated Science Assessment consideration
- Only outdoor pollution is regulated, conform to DQOs of ambient standards
- 1-hour averaging time supports studies of acute health effects and risk communication around short-term exposures
  - Should also allow researchers to investigate sub-hourly effects with high confidence in the measurements

Desired DQOs for research applications

- Limit of Detection: detect health effects at low concentrations
  - Some indoor settings
  - Diseases with no or low threshold concentration-response curves
  - 3-5 ppb for gases, 3 μg for PM_{10}
- Accuracy: quantification compared to a known standard (if gas, or filter if PM_{10}) within 10-15%
- Precision within 5-10%
- Zero drift (< 2ppb/day or 5ppb/year for gases)
  - Metal oxide sensors especially
- Linearity across range of realistic concentrations and one higher calibration point
- Measurement range globally relevant (at ground level population centers), also for met conditions
- Response time < 10 secs
- Flow rate within ± 5% if active
  - Especially low flow rate samplers, plus more sensitive flow logging

TABLE B–1 TO SUBPART B OF PART 53—PERFORMANCE LIMIT SPECIFICATIONS FOR AUTOMATED METHODS

Performance parameter	Units [1]	SO_2		O_3		CO		NO_2 (Std. range)	Definitions and test procedures
		Std. range [3]	Lower range [2 3]	Std. range [3]	Lower range [2 3]	Std. range [3]	Lower range [2 3]		
1. Range	ppm	0–0.5	<0.5	0–0.5	<0.5	0–50	<50	0–0.5	Sec. 53.23(a)
2. Noise	ppm	0.001	0.0005	0.0025	0.001	0.2	0.1	0.005	Sec. 53.23(b)
3. Lower detectable limit.	ppm	0.002	0.001	0.005	0.002	0.4	0.2	0.010	Sec. 53.23(c)
4. Interference equivalent									
Each interferent	ppm	±0.005	[4] ±0.005	±0.005	±0.005	±1.0	±0.5	±0.02	Sec. 53.23(d)
Total, all interferents.	ppm	–	–	–	–	–	–	0.04	Sec. 53.23(d)
5. Zero drift, 12 and 24 hour.	ppm	±0.004	±0.002	±0.004	±0.002	±0.5	±0.3	±0.02	Sec. 53.23(e)
6. Span drift, 24 hour									
20% of upper range limit.	Percent	–	–	–	–	–	–	±20.0	Sec. 53.23(e)
80% of upper range limit.	Percent	±3.0	±3.0	±3.0	±3.0	±2.0	±2.0	±5.0	Sec. 53.23(e)
7. Lag time	Minutes	2	2	2	2	2.0	2.0	20	Sec. 53.23(e)
8. Rise time	Minutes	2	2	2	2	2.0	2.0	15	Sec. 53.23(e)
9. Fall time	Minutes	2	2	2	2	2.0	2.0	15	Sec. 53.23(e)
10. Precision									

From: https://www.govinfo.gov/content/pkg/CFR-2016-title40-vol6/pdf/CFR-2016-title40-vol6-part53-subpartB-appB-id33.pdf

PM_{10} Considerations

Residential monitoring

- Outdoor
  - Micro scale, sources with high spatial variability like non-tailpipe traffic (brake and tire wear, resuspended road dust), unpaved roads, industries emitting dust (cement manufacturing etc..)
  - Urban/regional signals like wind-blown dust depending on area
- Indoor
  - Resuspended dust (indoor source)
  - Pollen and allergens

Personal monitoring

- Similar sources, high spatial variability and “personal cloud” effect
  - Measure in breathing zone, rather than near ground level or stationary, further away in room, to minimize exposure error

General issues

- *PM_{10} optical signals different than $PM_{2.5}$, need more relevant calibration aerosol for OPCs equations converting counts to mass*
- *More frequent optics cleaning compared to $PM_{2.5}$?*

Indoor relative to central site, outdoor gas concentrations: NYC example

Table 1. Distribution of weekly indoor and outdoor concentrations of gases (p.p.b.), $PM_{2.5}$ mass, its carbon fractions ($\mu g/m^3$) and elemental components (ng/m^3).

Pollutant	*Indoor concentration*			*Outdoor concentration*		
	N	*Mean*	*SD*	N	*Mean*	*SD*
Units: p.p.b.						
NO_2	126	28.5	13.7	130	24.6	5.6
SO_2	126	0.3	0.6	130	6.2	4.1
O_3	126	2.8	3.7	129	19.8	8.3

Sources of indoor air pollution in New York City residences of asthmatic children

Rima Habre[1], Brent Coull[1,2], Erin Moshier[3], James Godbold[3], Avi Grunin[4], Amit Nath[5], William Castro[5], Neil Schachter[5], Annette Rohr[6], Meyer Kattan[7], John Spengler[1] and Petros Koutrakis[1]

Journal of Exposure Science and Environmental Epidemiology (2013), 1–10

NO_2 Considerations

Residential monitoring

- Outdoor
  - Capture spatially variable traffic tailpipe emissions signals (NO_x more variable than NO_2)
  - Transported "aged" NO_2
- Indoor
  - Gas stoves as a major source, usually high levels indoors when present
  - In absence of gas stoves or other major sources, can indicate impact of traffic indoors

Personal monitoring

- Likely impacted by traffic/in-transit activities, other fuel combustion, and indoor combustion sources
- Detection limit issues at sub-hour frequency?
- Chemiluminescence FRM difficult to miniaturize (unlike O_3 UV absorption for example)

General issues

- *Detection limits for minute to hourly measurements?*

SO_2 Considerations

Residential monitoring

- Outdoor
  - Capture point and area sources
  - Usually industry/transportation related, sulfur in fuel
  - EJ communities living near sources or major truck transportation corridors
- Indoor
  - Limited to no indoor sources
  - Very low concentrations indoors, detection limit issues

Personal monitoring

- Time-activity weighted exposure likely very low, detection limit issues
- Occupational settings

General issues

- *Detection limits for deployments other than outdoor, stationary, or outdoor near-source or fence line monitoring?*

CO Considerations

Residential monitoring

- Outdoor
  - Microscale hotspots like major intersections in urban areas, street canyon effects with high-rise buildings, near major freeways, poorly ventilated parking lots
  - Signal diluted away at central sites
- Indoor
  - Safety purposes (incomplete combustion) at high levels
  - Homes, schools or offices sited close to outdoor hotspots: productivity and health issues
  - Risk factor for individuals with cardiovascular disease at lower levels

Personal monitoring

- Safety purposes (CO poisoning, occupational settings)
- Risk factor for individuals with cardiovascular disease at lower levels

General issues

- *Sensors well-developed for safety applications to detect high concentrations, but are detection limits sufficient for indoor/personal exposures or general ambient levels?*

Other features and design recommendations: *Same as 1st workshop, emphasizing…*

Wearability/Usability

- User-centered design principles, 'real-life compatible'
- 'Smart' calibration kits or options
  - Automatic self-calibration for zero drift?
  - Sensor-manufacturer designed quick turnaround calibration plan? Especially for exposure and health research studies…
    - Pre-, during- and post- deployment calibration exercises not very feasible while running a study
  - Standardized test protocols and more diverse test aerosol(s) for PM (reflect more representative aerosol size distribution and composition than Arizona Road Dust)

Data processing/communication

- Ability to communicate *securely* and in real-time
- Capture QA/QC metadata + GPS + RH/Temp + wear compliance + noise + light + other environmental parameters measured by smartphones or other paired devices?
- Capacity to store data for 1hr+ when connection lost
- 'Plug-and-play' ability, advertise MAC address etc…
  - Play well with other sensors in a system or platform!

Need for acute exposure and health studies

Understand exposure determinants and health associations

- At minute to hourly levels
- Peaks and transient exposures, specific source signals
- Important for acute outcomes such as cardiac events, arrythmias, heart rate variability, asthma attacks, etc..
- At individual level, not just population level

Inform data visualization strategies and risk communication

- Direct comparison of minute-level low-cost sensor readings to AQI is misleading and inaccurate
- Data visualization key for engaging participants, but care in influencing behavior or biasing research
- Sensor/app developers should take care in how/what to present and communicate around

Pollutant-specific considerations: Most sensitive groups per AQI guidance

When this pollutant has an index value above 100 * * *	Report these sensitive groups * * *
Ozone	Children and people with asthma are the groups most at risk.
$PM_{2.5}$	People with respiratory or heart disease, the elderly and children are the groups most at risk.
PM_{10}	People with respiratory disease are the group most at risk.
CO	People with heart disease are the group most at risk.
SO_2	People with asthma are the group most at risk.
NO_2	Children and people with respiratory disease are the groups most at risk.

40 CFR Part 58, Ambient air quality surveillance, Appendix G to Part 58—Uniform Air Quality Index (AQI) and Daily Reporting
https://www.ecfr.gov/cgi-bin/text-idx?SID=c7fae1149eb6eeaa96ea607c0b871570&mc=true&node=ap40.6.58.0000_0nbspnbspnbsp.g&rgn=div9

Thank You

- Los Angeles PRISMS Center webinar by Alex Bui (PI) and Rima Habre for the NIEHS Exposure Science and the Exposome Webinar Series: https://www.youtube.com/watch?v=6y0tzsfApw4

- Current list of reference and equivalent methods for criteria air pollutants: https://www3.epa.gov/ttn/amtic/files/ambient/criteria/AMTIC_List_June_2017_update_6-19-2017.pdf