



Consumer-grade IAQ sensors: *Complications of CO₂ ventilation measurements*

Dustin Poppendieck, National Institute of Standards and Technology

Disclaimer

- *Certain commercial equipment, instruments, websites, or materials are identified in this paper. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.*

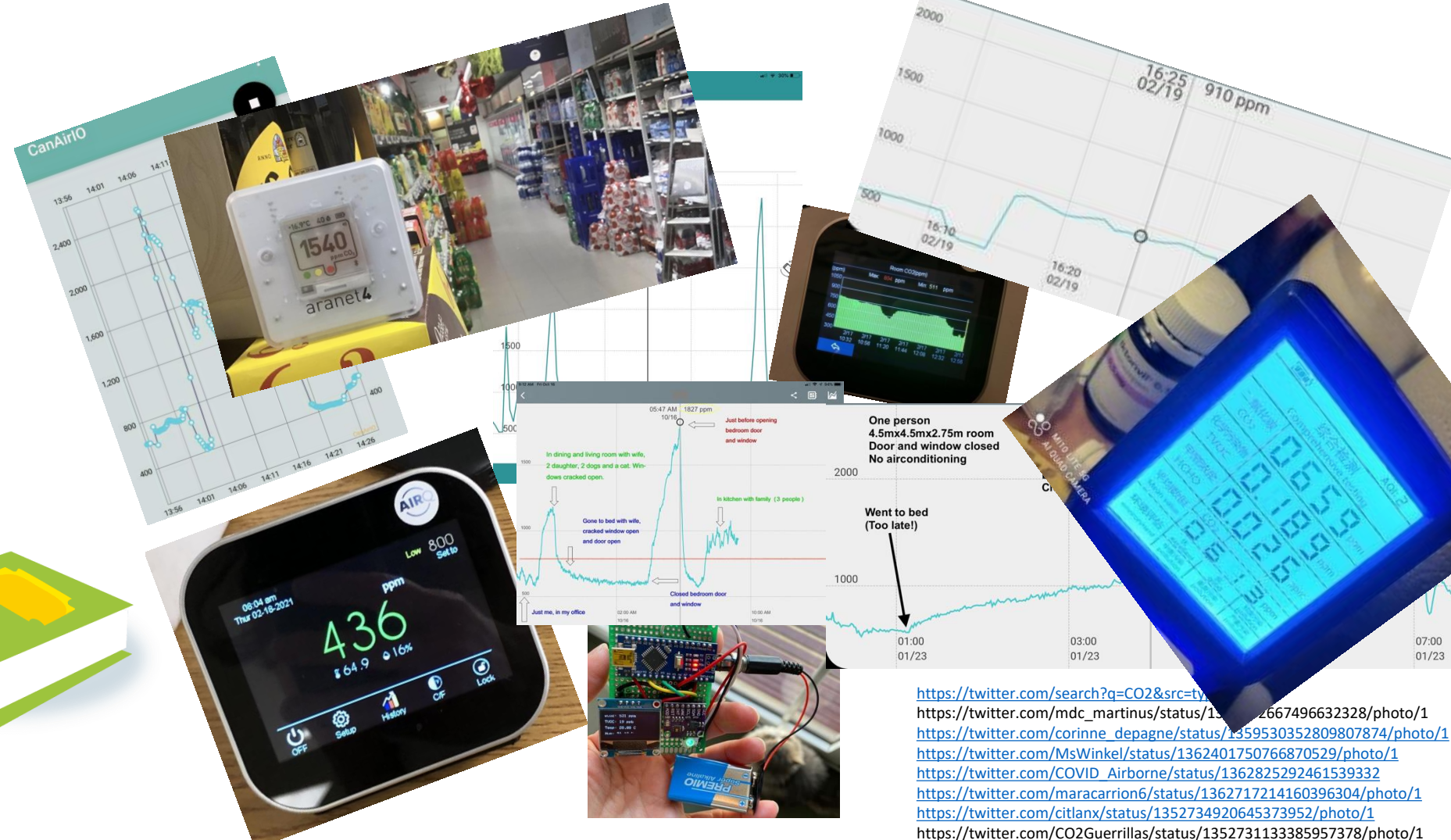


Educational Tools

- Ownership
- Action
 - Source removal
 - Ventilation
 - Filtration



Educational Tools

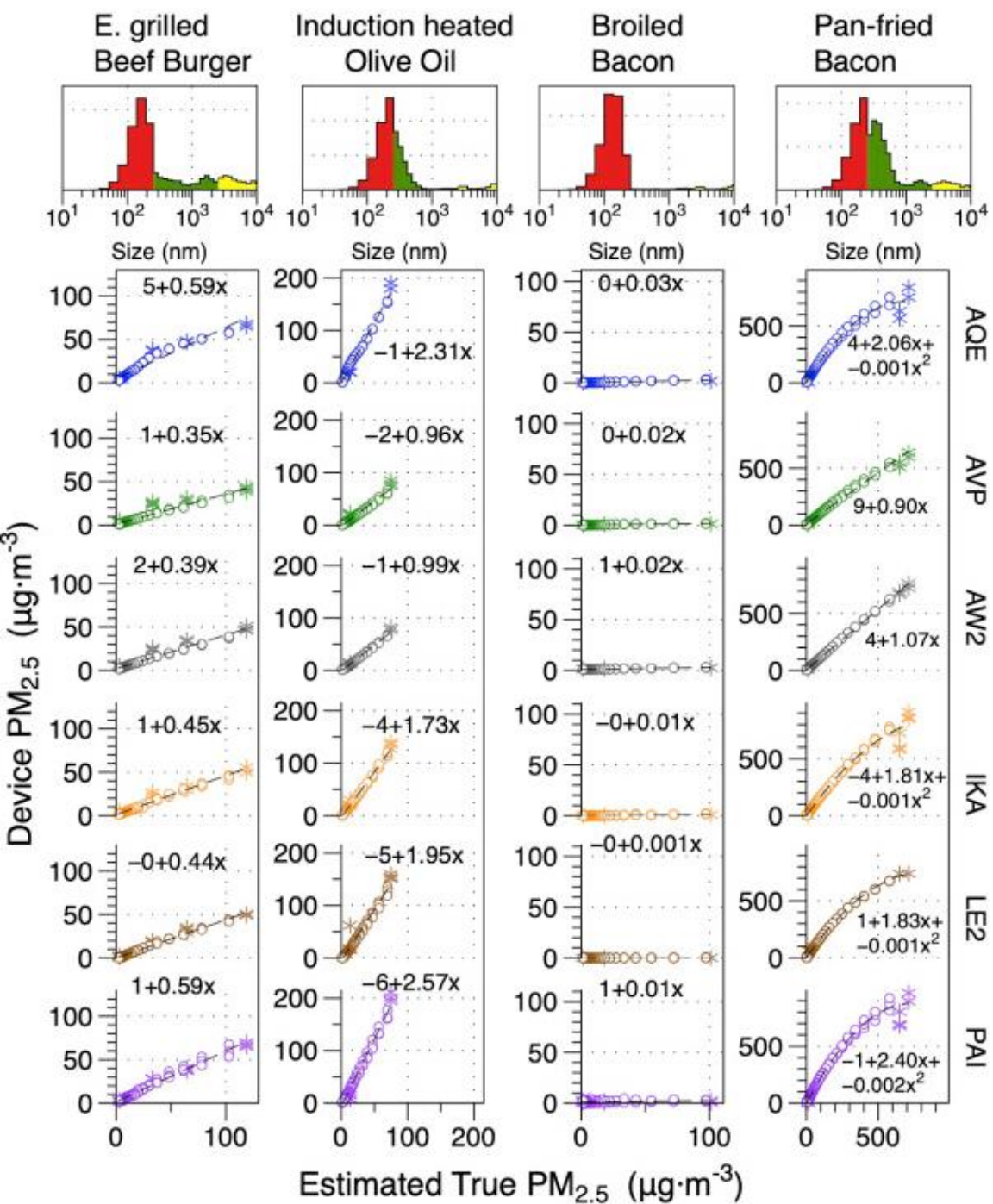


<https://twitter.com/search?q=CO2&src=ty>
https://twitter.com/mdc_martinus/status/1352731133385957378/photo/1
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<https://twitter.com/citlanx/status/1352734920645373952/photo/1>
<https://twitter.com/CO2Guerrillas/status/1352731133385957378/photo/1>



What does it all mean?

- Health values
 - Time Weighted/Instantaneous
- Accuracy/Precision
- Ventilation



Building and Environment

Volume 171, 15 March 2020, 106654



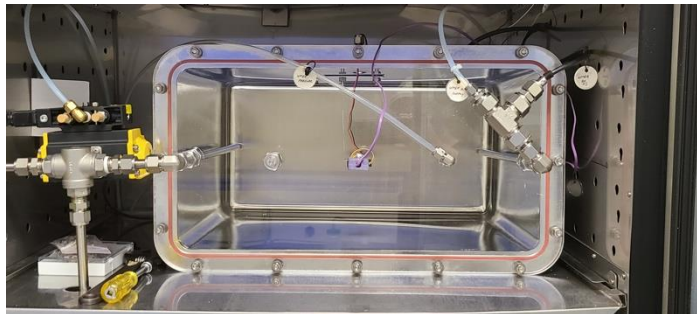
Performance of low-cost indoor air quality monitors for $PM_{2.5}$ and PM_{10} from residential sources

Zhiqiang Wang^a, William W. Delp^b, Brett C. Singer^b



Test Method for Evaluating PM_{2.5} Monitors

- Class III FEM Reference Monitor
 - 20 nm to 20 μm
 - Gravimetrically calibrated
- Challenge PM_{2.5}
 - Sodium chloride (1.5 μm to 1.8 μm)
 - Polystyrene latex spheres (1 μm)
- Chamber system
 - Steady state values

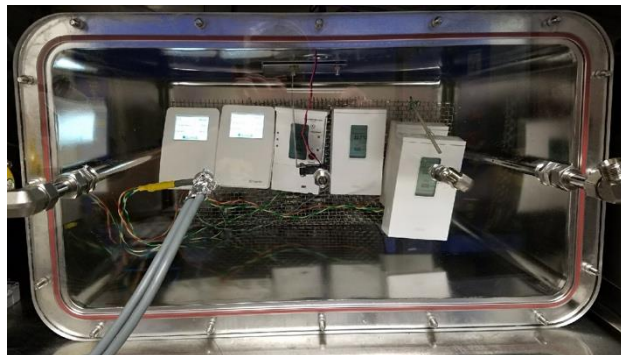


- Process
 - Five step concentration ramp
 - 10 $\mu\text{g m}^{-3}$ to 300 $\mu\text{g m}^{-3}$
 - Inorganic then organic
 - RH and Temp variation
 - 40 % to 80 %
 - 20 °C and 30 °C
 - Interferent testing
 - Arizona Test Dust (PM₁₀)
 - 10 $\mu\text{g m}^{-3}$ to 150 $\mu\text{g m}^{-3}$
 - Temperature cycling
 - 10 °C to 50 °C 143 times
 - Repeating concentration ramp



Test Method for Evaluating CO₂ Monitors

- Reference Monitor
 - 0 ppm_v to 10,000 ppm_v
 - Calibrated to certified cylinder
 - Drying system
- Chamber system
 - Steady state values



- Process
 - Five step concentration ramp
 - 450 ppm_v to 5,000 ppm_v
 - RH and Temp variation
 - 40 % to 80 %
 - 20 °C and 50 °C
 - Interferent testing
 - Relative humidity 20 % to 90 %
 - Temperature cycling
 - 10 °C to 50 °C 143 times
 - Repeating concentration ramp

Consumer-grade sensors report concentrations in ppm_v. SI units are $\mu\text{g m}^{-3}$. 1000 ppm_v CO₂ = 929 $\mu\text{g CO}_2 \text{ m}^{-3}$ at 25 °C and 1 atm.



So that will be it
then, right?

- Just data. Need accreditation organizations.
- Re-zeroing algorithms for CO₂
- Long term drift?
 - 1 year plus?

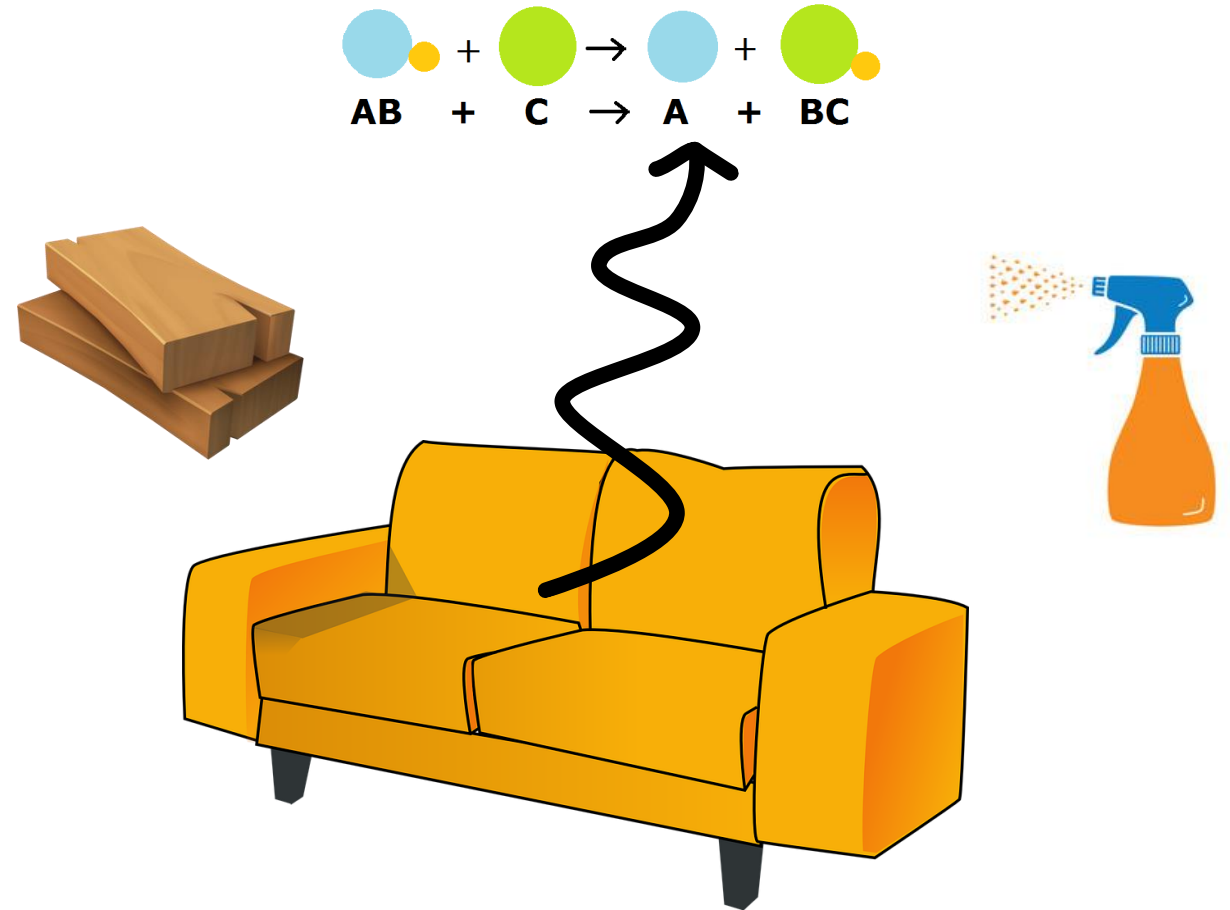
Using CO₂ as a Ventilation Clue



The story of 10 Complications

Using CO₂ as a Ventilation Clue

CO₂  IAQ



Complication #1

Using CO₂ as a Ventilation Clue

LÍMITE DE CO₂ COMO INDICADOR INDIRECTO DE RIESGO DE INFECCIÓN

El riesgo de infección (aerosoles) es proporcional a la concentración de CO₂:

- Se evalúa mediante la diferencia de CO₂ entre interior y exterior (ΔCO_2).
- Si $\Delta\text{CO}_2 > 0$, ya existe riesgo.

NIVELES DE CO ₂ (CO _{2,ext} ≈ 420 ppm)	ΔCO_2 int-ext	% del aire inhalado	Si se instala filtro HEPA	
≥ 1000 ppm	600 ppm	1,47%	límite	Límite de la OMS
≥ 900 ppm	500 ppm	1,21%	atención	Límite del RITE (IDA 2)
≥ 800 ppm	400 ppm	0,96%	admisible	-
≥ 700 ppm	300 ppm	0,71%	adecuado	-
< 700 ppm	300 ppm	0,71%	adecuado	Harvard/Guías IDAEA-CSIC-LIFTEC
< 550 ppm	150 ppm	0,33%	adecuado	Pasillos y ZZCC (espacios "aliviadero")

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https://drive.google.com/file/d/1jFavucO98vMz5_LpKtnDXBfDZvWIMLcL/view



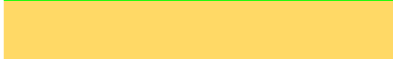


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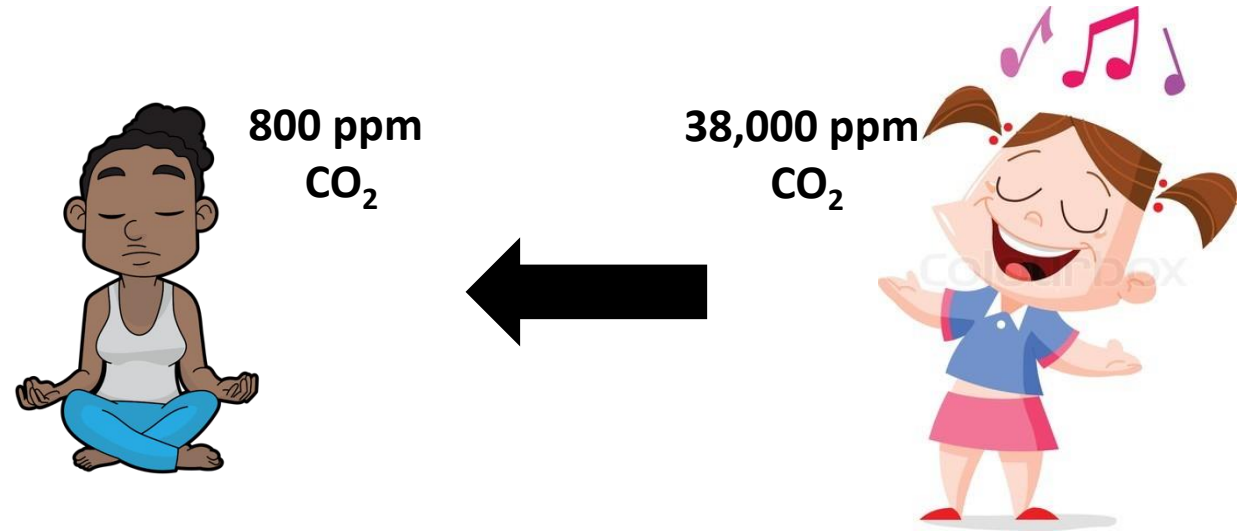
HEALTHY BUILDINGS
FOR HEALTH | schoolsforhealth.org

TARGET IS AT LEAST 5 TOTAL AIR CHANGES PER HOUR

	<i>Ideal (6 ACH)</i>
	<i>Excellent (5-6 ACH)</i>
	<i>Good (4-5 ACH)</i>
	<i>Bare minimum (3-4)</i>
	<i>Low (<3 ACH)</i>

<https://schoolsforhealth.org/wp-content/uploads/sites/19/2020/08/Harvard-Healthy-Buildings-program-How-to-assess-classroom-ventilation-08-28-2020.pdf>

Using CO₂ as a Ventilation Clue



Full Access

Risk of indoor airborne infection transmission estimated from carbon dioxide concentration

S. N. Rudnick, D. K. Milton

First published: 24 October 2003 | <https://doi.org/10.1034/j.1600-0668.2003.00189.x> | Citations: 143

$$\text{Rebreathed Fraction} = \frac{(C_{\text{average}} - C_{\text{outside}})}{C_{\text{breath}}}$$

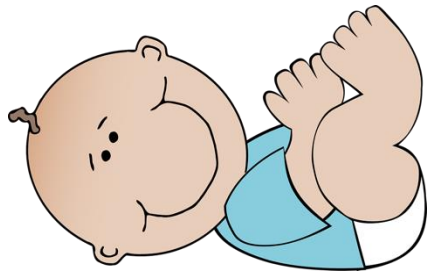
$$\text{Rebreathed Fraction} = \frac{(800 \text{ ppm}_v - 420 \text{ ppm}_v)}{38,000 \text{ ppm}_v}$$

$$\text{Rebreathed Fraction} = 1.0 \%$$

$$C_{\text{average}} = 2,000 \text{ ppm}_v \Rightarrow 4.2\%$$

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Using CO₂ as a Ventilation Clue

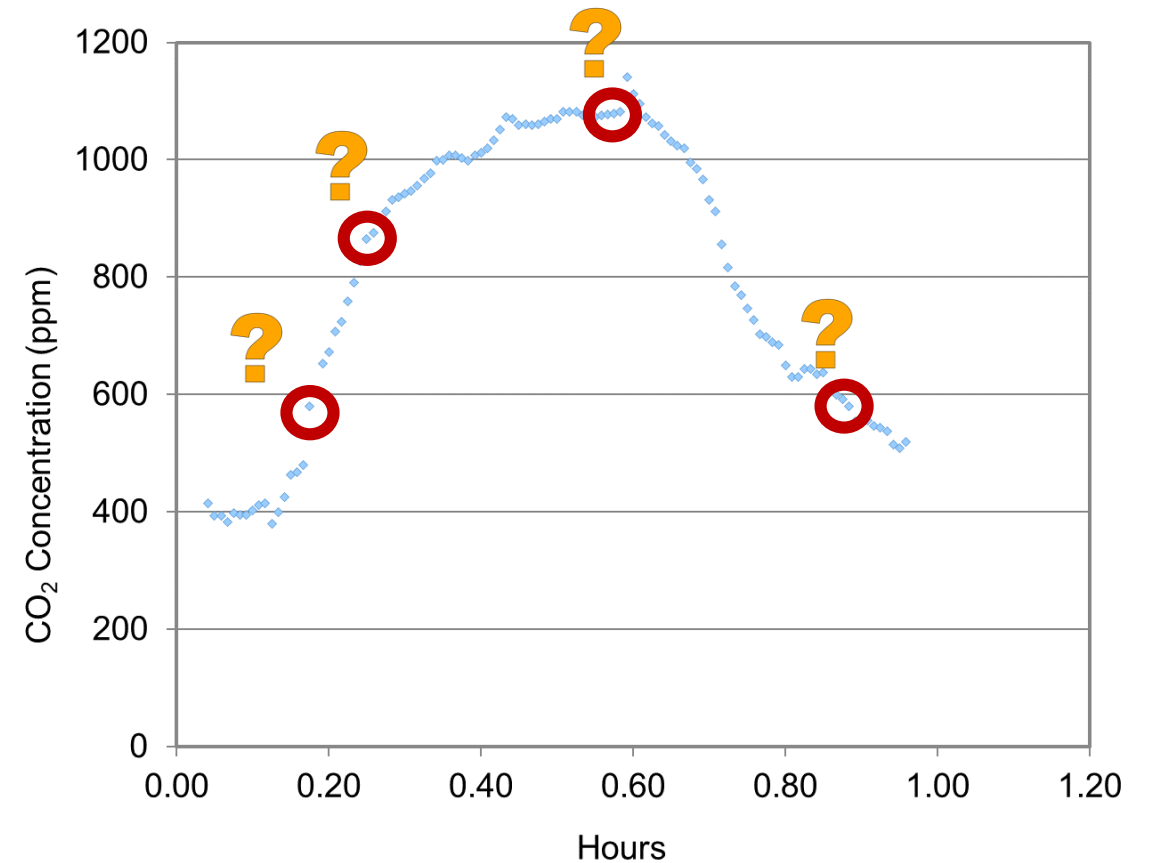


Complication #2

Using CO₂ as a Ventilation Clue



650 ppm



Complication #3

Data from student lab at Humboldt State University

Using CO₂ as a Ventilation Clue



Complication #4

Using CO₂ as a Ventilation Clue

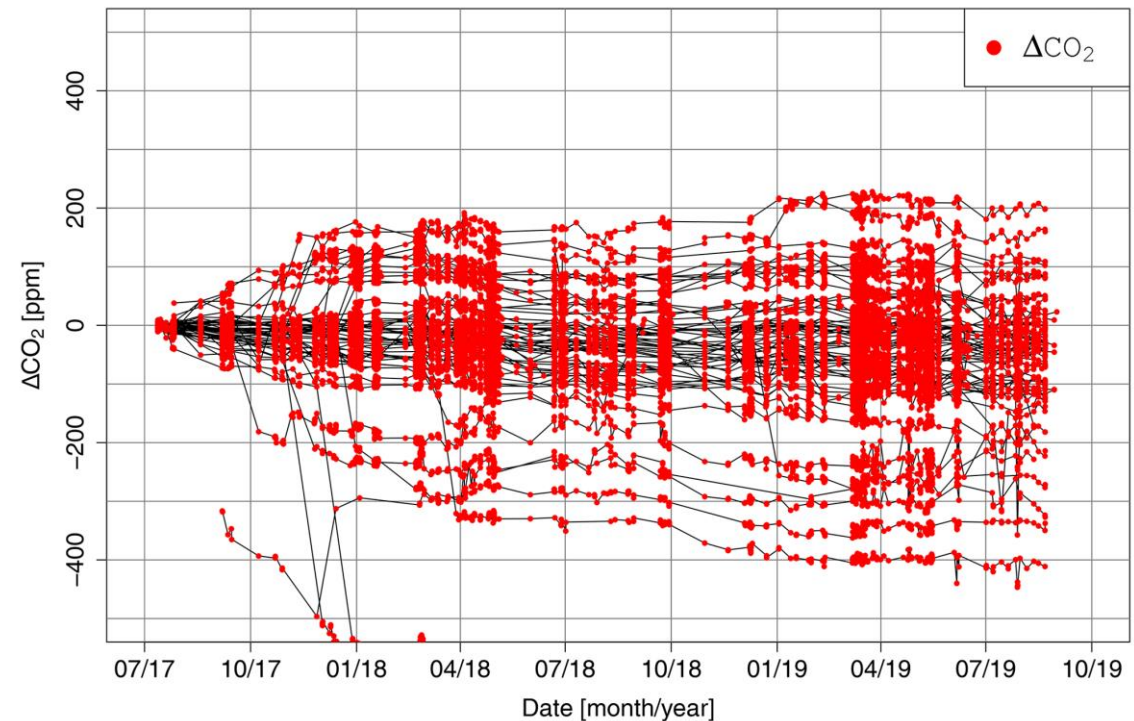
Atmos. Meas. Tech., 13, 3815–3834, 2020
<https://doi.org/10.5194/amt-13-3815-2020>
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Atmospheric
Measurement
Techniques
Open Access
EGU

Integration and calibration of non-dispersive infrared (NDIR) CO₂ low-cost sensors and their operation in a sensor network covering Switzerland

Michael Müller¹, Peter Graf¹, Jonas Meyer², Anastasia Pentina³, Dominik Brunner¹, Fernando Perez-Cruz³, Christoph Hüglin¹, and Lukas Emmenegger¹



Complication #5

Using CO₂ as a Ventilation Clue

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Using CO₂ as a Ventilation Clue

Space	Occupancy	Ventilation Rate ASHRAE 62.1 (L/s/person)	Outdoor Air Change rate (h ⁻¹)	Steady State or Mean Peak CO ₂ Concentration ppm _v	Reference
Ideal Classroom Meeting Standards (5- to 8-year-olds)	24 students 1 instructor	7.4	~2.6 ^a	828 ^b	 <p>ORIGINAL ARTICLE Open Access © ⓘ</p> <p>Carbon dioxide generation rates for building occupants</p> <p>A. Persily, L. de Jonge</p> <p>First published: 20 March 2017 https://doi.org/10.1111/ina.12383 Citations: 90</p>
10 Actual California Classrooms	N/A	2.6 – 7.1	N/A	1,140 - 2,380	 <p>Original Article Free Access</p> <p>Association of classroom ventilation with reduced illness absence: a prospective study in California elementary schools</p> <p>M. J. Mendell, E. A. Elzeva, M. M. Davies, M. Spears, A. Lobscheid, W. J. Fisk, M. G. Apte</p> <p>First published: 19 March 2013 https://doi.org/10.1111/ina.12042 Citations: 99</p>

^aClassroom volume values from Ng et. al. 2020

https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=930986

^bAssuming outdoors 420 ppm

Consumer-grade sensors report concentrations in ppm_v. SI units are µg m⁻³. 1000 ppm_v CO₂ = 929 µg CO₂ m⁻³ at 25 °C and 1 atm.

Using CO₂ as a Ventilation Clue



Full Access

Association between substandard classroom ventilation rates and students' academic achievement

U. Haverinen-Shaughnessy, D. J. Moschandreas, R. J. Shaughnessy

First published: 24 August 2010 | <https://doi.org/10.1111/j.1600-0668.2010.00686.x> | Citations: 133

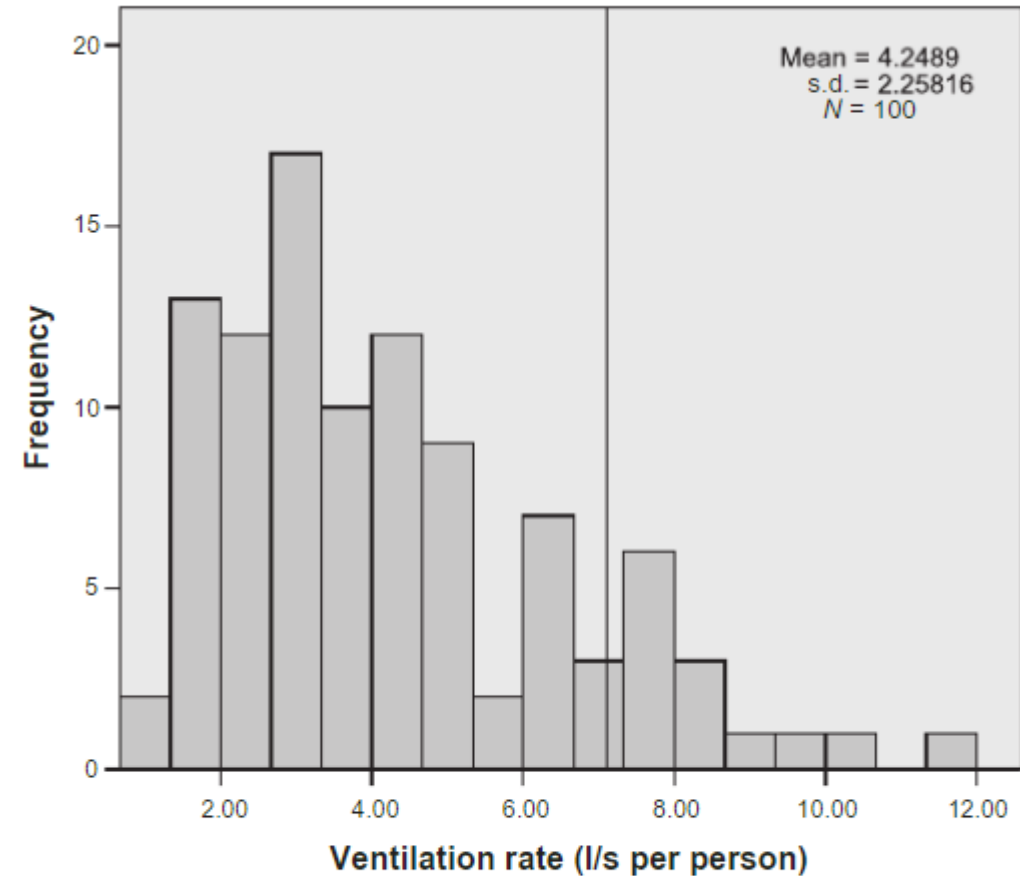


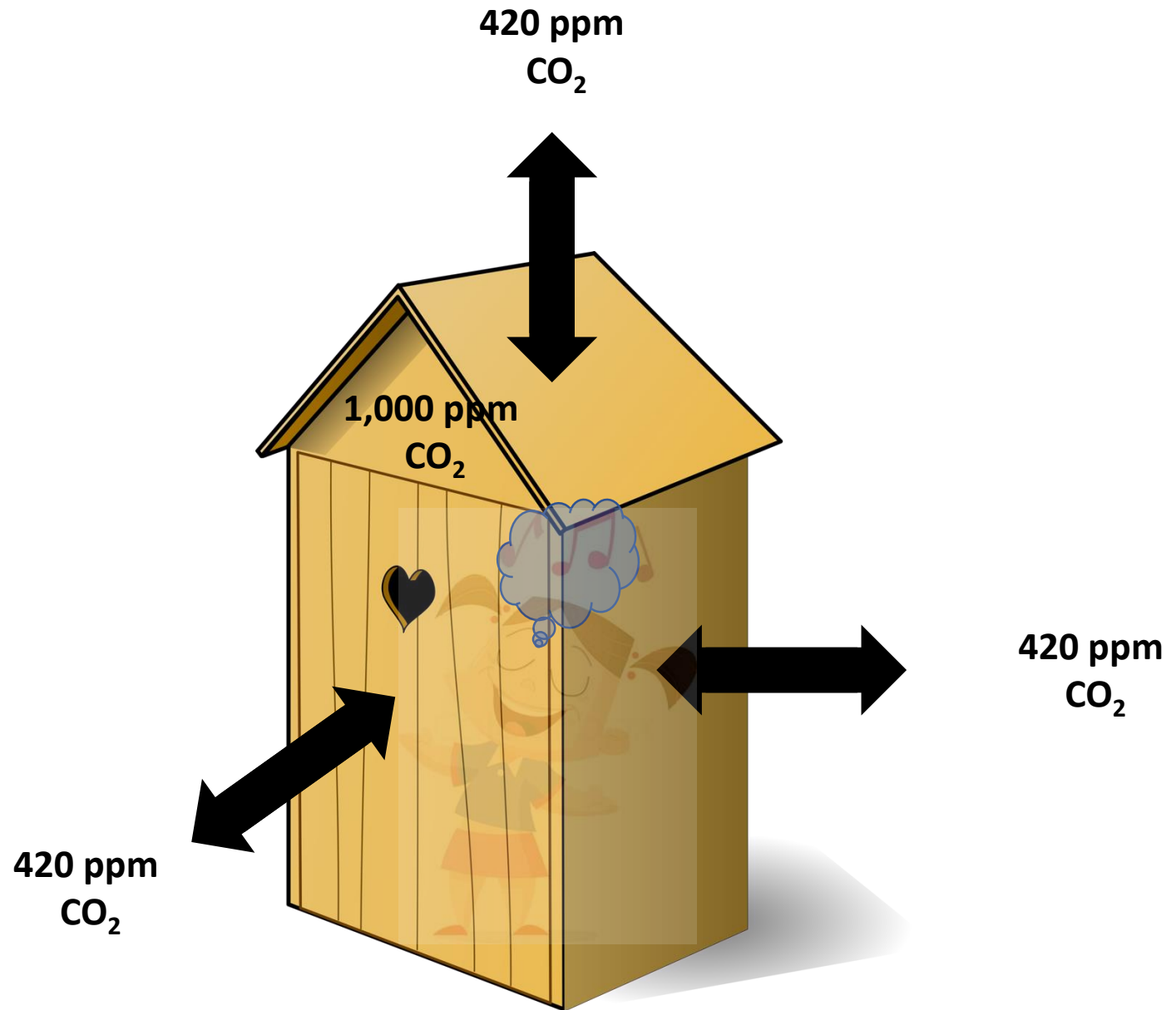
Fig. 1 Ventilation rate distribution (vertical line corresponds to ASHRAE recommended minimum)

Using CO₂ as a Ventilation Clue

Mass Balance

$$\text{CO}_2 \text{ in room} = (\text{CO}_2 \text{ In}) - (\text{CO}_2 \text{ Out})$$

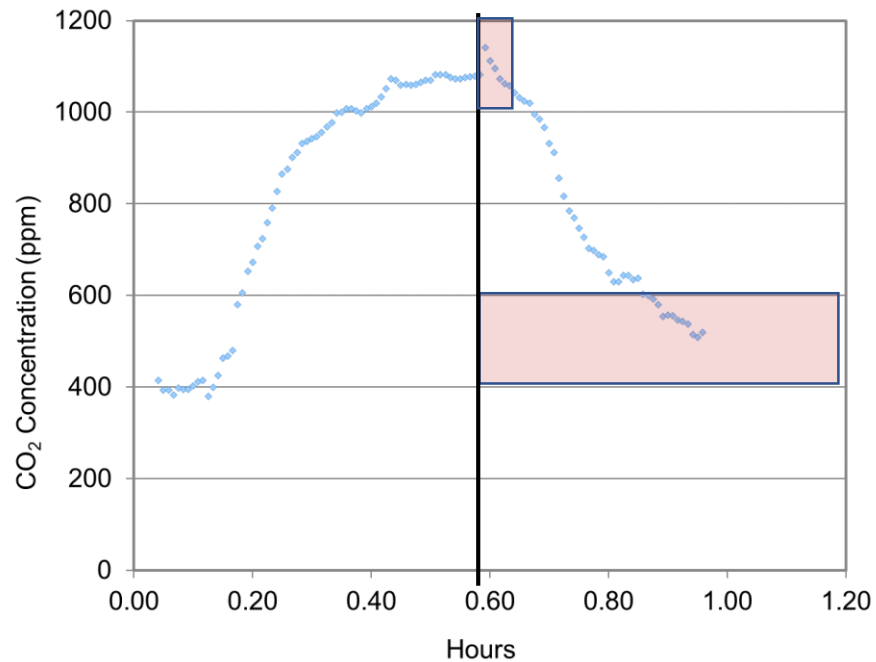
Assumes well-mixed room



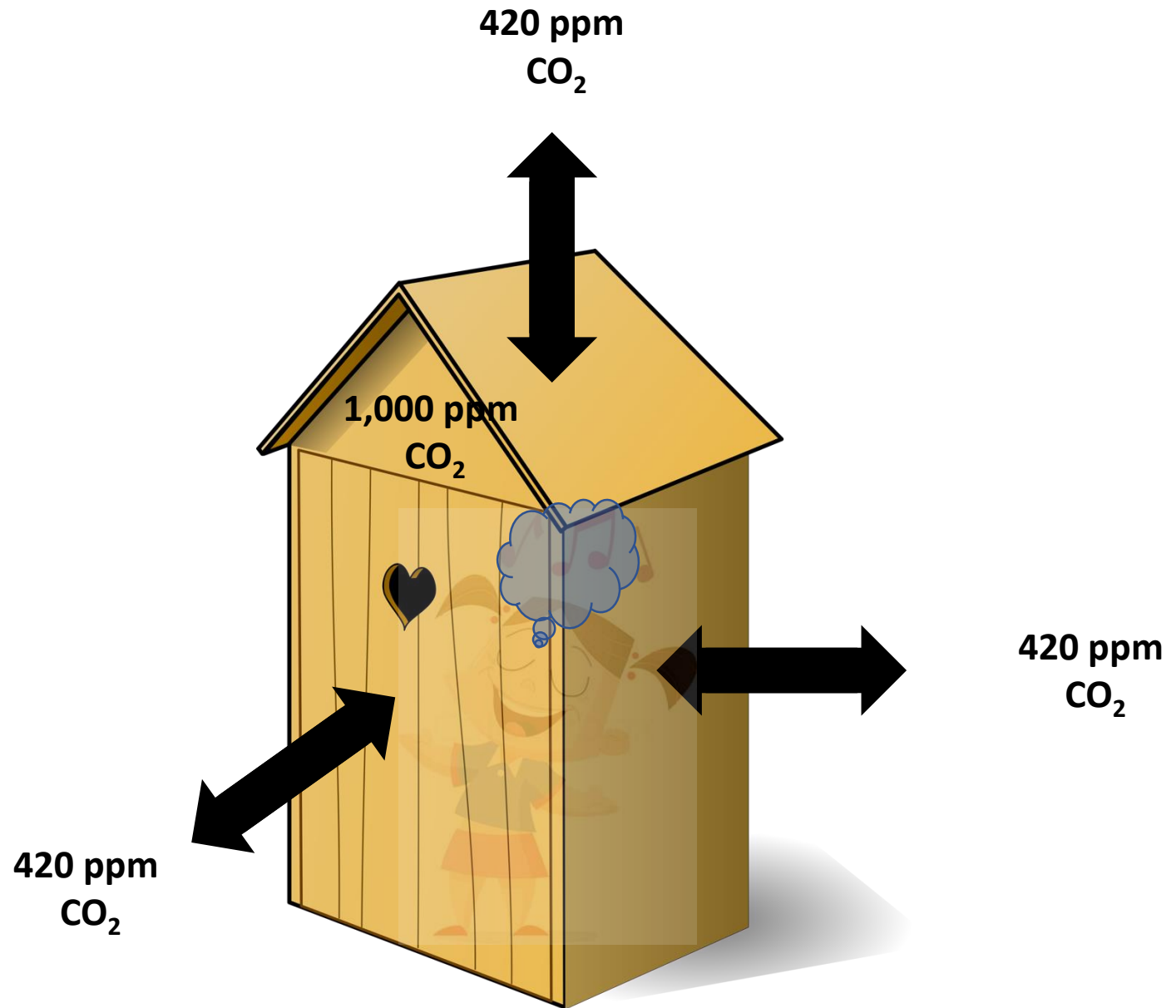
Using CO₂ as a Ventilation Clue



Using CO₂ as a Ventilation Clue



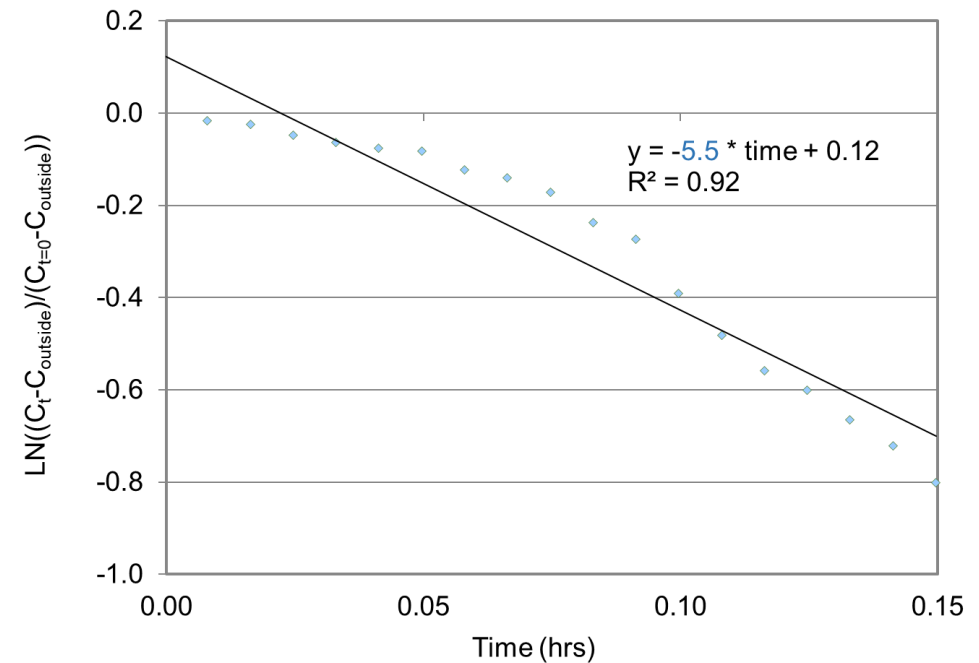
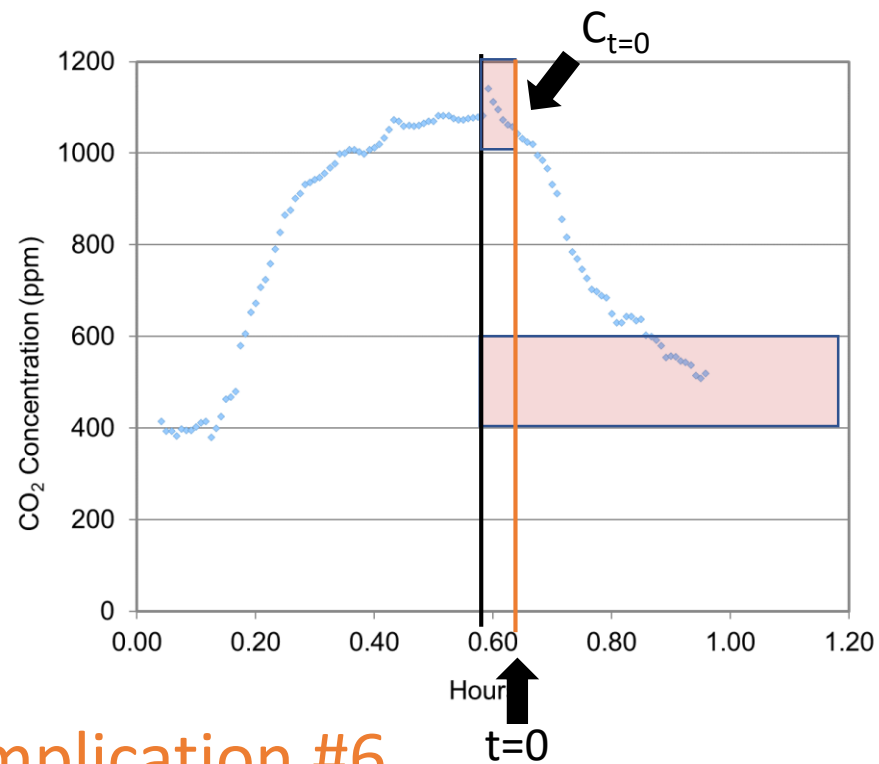
Data from student lab at Humboldt State University



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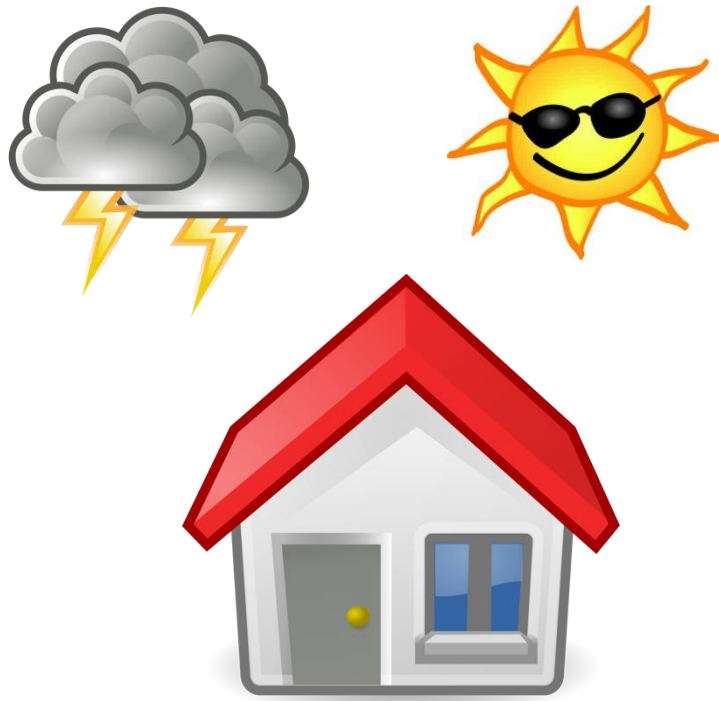
Using CO₂ as a Ventilation Clue

$$\ln \left[\frac{(C_t - C_{outside})}{(C_{t=0} - C_{outside})} \right] \text{ vs. } t$$



Complication #6

Using CO₂ as a Ventilation Clue



Complication #7

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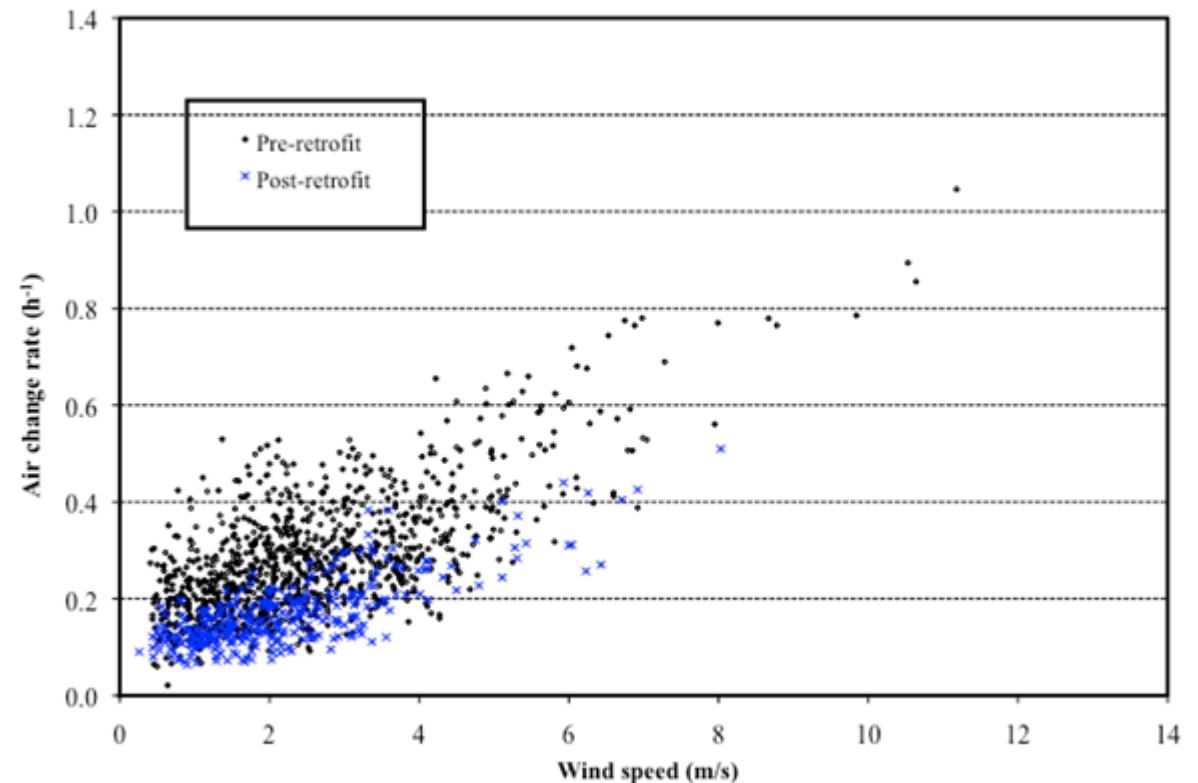


Energy and Buildings
Volume 43, Issue 11, November 2011, Pages 3059-3067

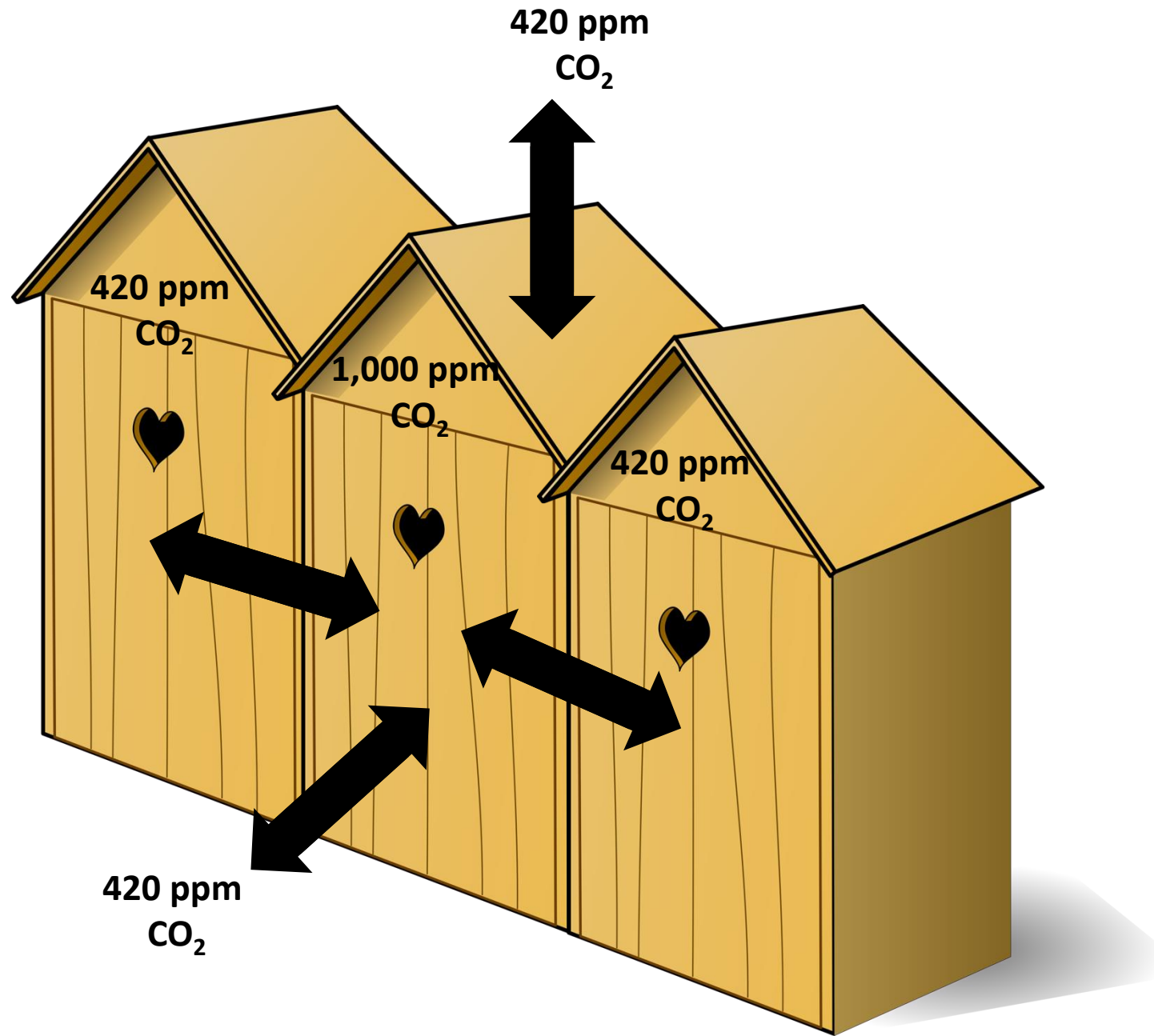


Impacts of airtightening retrofits on ventilation rates and energy consumption in a manufactured home

Steven Nabinger , Andrew Persily 

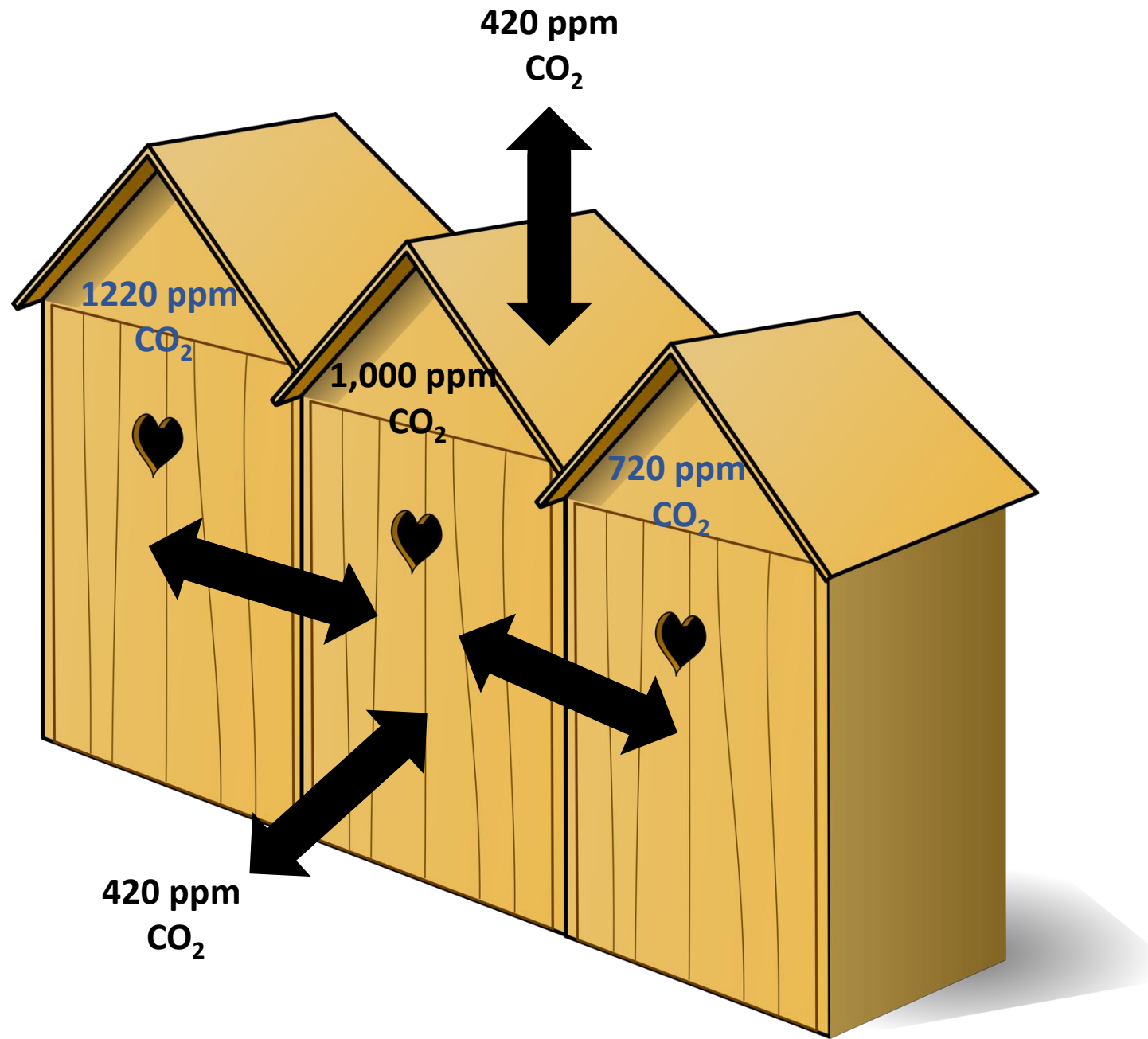


Using CO₂ as a Ventilation Clue



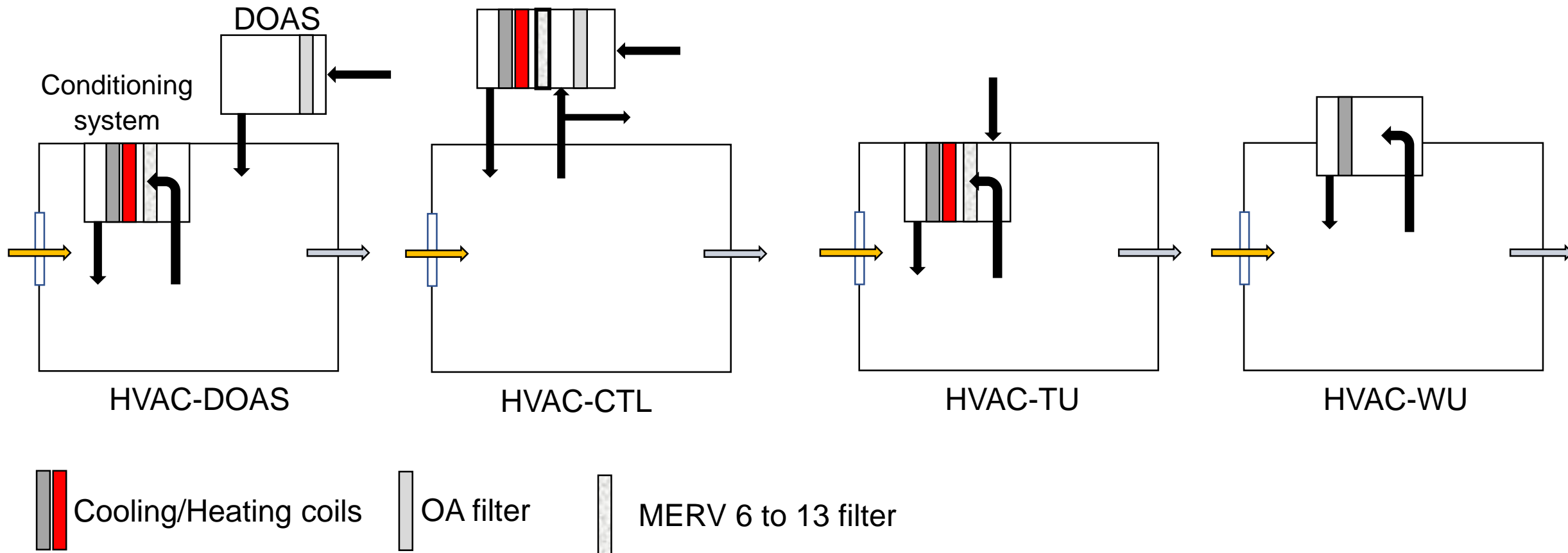
Complication #8

Using CO₂ as a Ventilation Clue



Complication #8

Using CO₂ as a Ventilation Clue



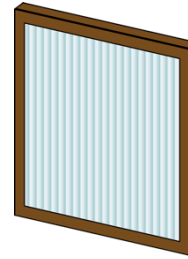
Complication #9 Infiltration Air leaving zone through leakage

Using CO₂ as a Ventilation Clue

**Effective Air
Change Rate
Estimation
for Particle
Removal**



CO₂ Measurement



Portable HEPA Filter



HVAC MERV 13 Filter

Complication #10

<https://www.tsi.com/products/ventilation-test-instruments/alnor/alnor-capture-hoods/alnor-balometer-capture-hood-ebt731/>



Conclusion

Ventilation and Consumer Grade Cost Sensors:

It's complicated