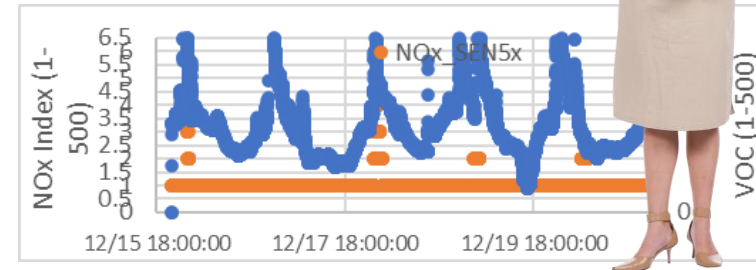# Fusing Low-cost Sensor Data, Occupant Feedback and Energy Use for Optimal IAQ in Residential Settings

Dennis Heidner, Rextor Group
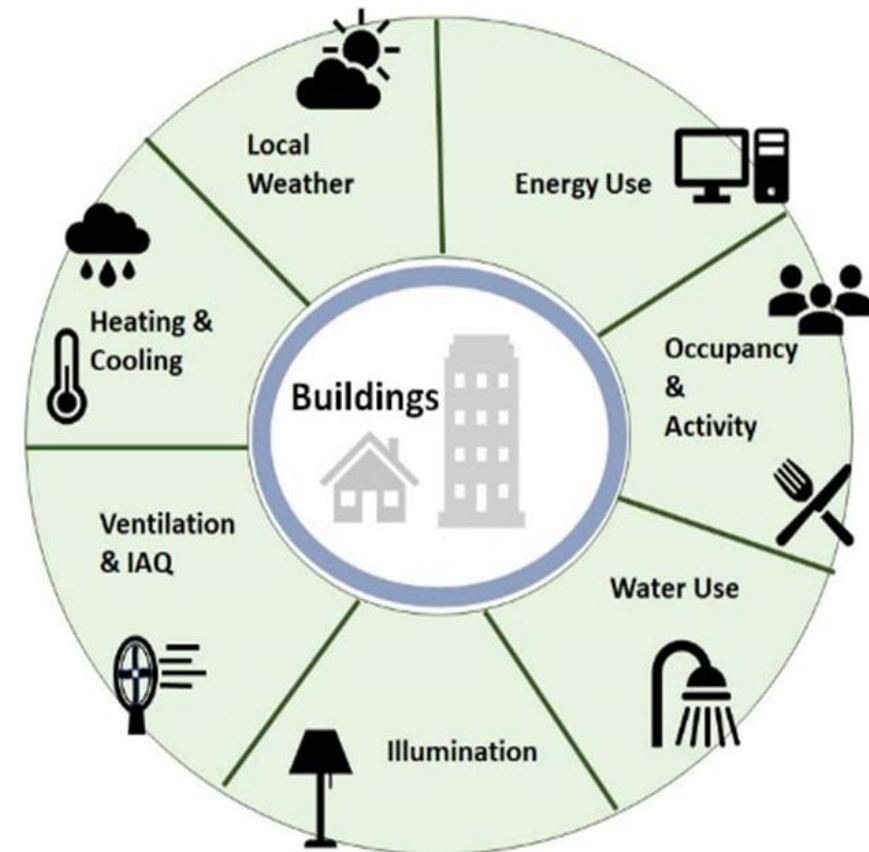
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IAQ is part of the indoor system

Indoor Environment Quality (IEQ) includes :

- Indoor Air Quality of the occupied space
- Thermal comfort of the space
- Sound in the occupied space
- Lighting in the occupied space
- Shape and form of the space

Our perception of the IEQ is impacted by more than just the IAQ and vice versa

Presentation Objectives

The motivation for the presentation

- Encourage ASIC community into continuing strong support of younger students

- Encourage students grades 8-12 to study and design with sensors

- Encourage college undergraduates to study and design with low cost sensors for both outdoor and indoor air quality

- Hook the next generation that are focused on AI & ML to apply that to "not so snazzy" indoor air quality and building sciences.

- Identify problem areas!

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The bad & ugly indoor pollutants

*

Table 1. Pollutants considered for inclusion in the WHO indoor air quality guidelines by the WHO working group in October 2006

Group 1. Development of guidelines recommended	Group 2. Current evidence uncertain or not sufficient for guidelines
Benzene *	Acetaldehyde
Carbon monoxide *	Asbestos *
Formaldehyde *	Biocides, pesticides *
Naphthalene *	Flame retardants
Nitrogen dioxide *	Glycol ethers
Particulate matter ($PM_{2.5}$ and PM_{10}) *	Hexane
Polycyclic aromatic hydrocarbons, especially * benzo-[a]-pyrene	Nitric oxide *
Radon *	Ozone *
Trichloroethylene	Phthalates *
Tetrachloroethylene*	Styrene *
	Toluene *
	Xylenes*

Source: WHO Regional Office for Europe (5).

Pollutants * were discovered in a family home of 60+ years, prior to moving out.

From, "WHO guidelines for indoor air quality: selected pollutants",
https://iris.who.int/bitstream/handle/10665/260127/9789289002134-eng.pdf

What is acceptable per ANSI / ASHRAE

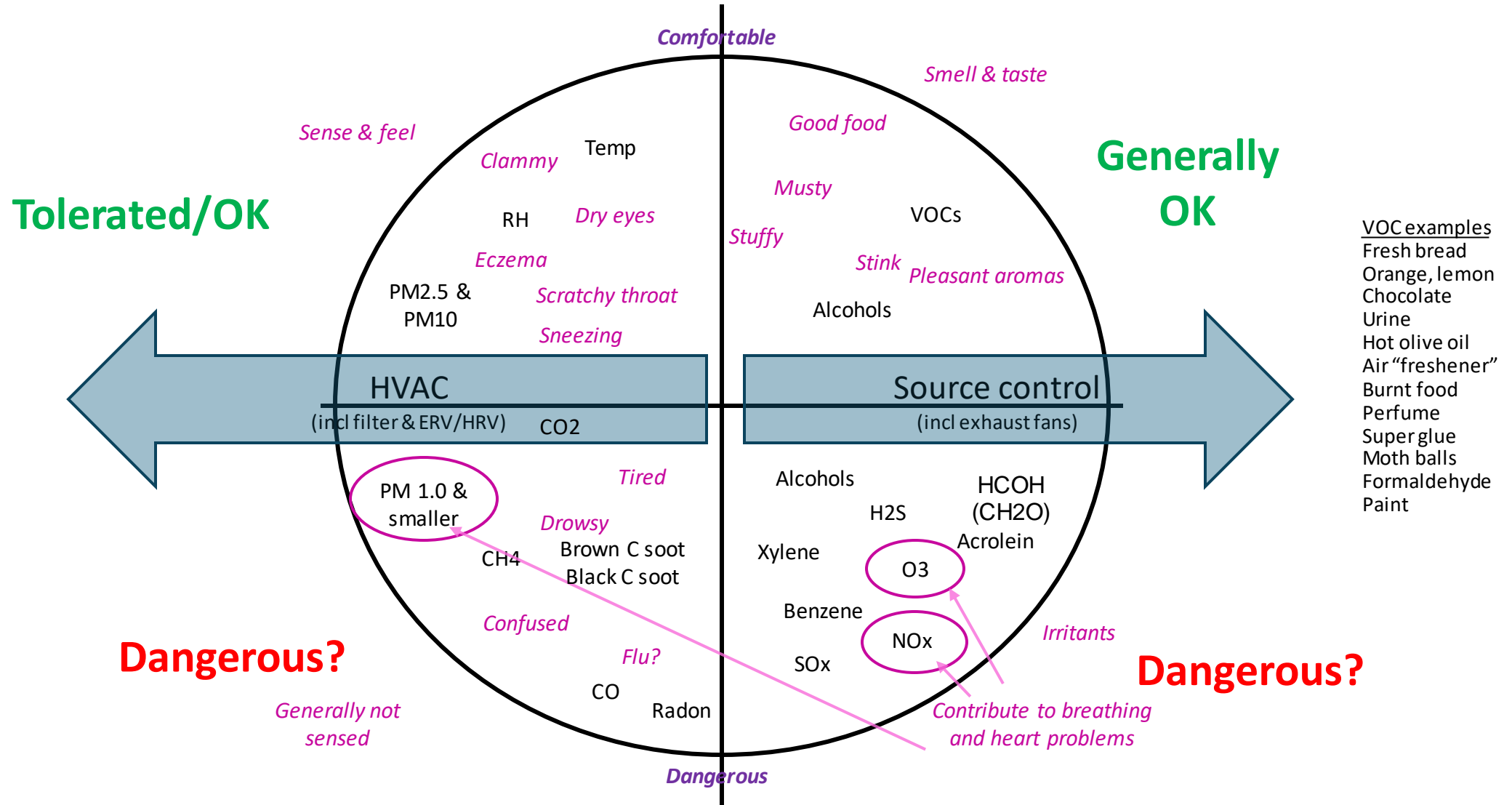ANSI/ASHRAE STD 62.2-2022, 3.1 Terms "acceptable indoor air quality:"

"Air toward which a substantial majority of occupants express no dissatisfaction with respect to odor and sensory irritation and in which there are not likely to be contaminants that pose a health risk."

Remember "dissatisfaction with respect to odor and sensory" and

"pose a health risk"

ASHRAE has local professional chapters nationwide and student chapters at many engineering schools.

(Full document available from ASHRAE.)

STEM Thinking

IAQ: a complex subset of IEQ

Comfortable

Smell & taste

Good food

Sense & feel

Clammy Temp

Musty

VOCs

Stuffy

Dry eyes

RH

Stink Pleasant aromas

Eczema

Scratchy throat

PM2.5 & PM10

Alcohols

Sneezing

Tolerated/OK

Generally OK

HVAC
(incl filter & ERV/HRV)

Source control
(incl exhaust fans)

CO2

Tired

Alcohols HCOH (CH2O)

Drowsy

H2S

PM 1.0 & smaller

Acrolein

CH4 Brown C soot
Black C soot

Xylene

O3

Confused

Benzene

NOx

Flu?

SOx

Irritants

CO Radon

Dangerous?

Dangerous?

Generally not sensed

Contribute to breathing and heart problems

Dangerous

VOC examples
Fresh bread
Orange, lemon
Chocolate
Urine
Hot olive oil
Air "freshener"
Burnt food
Perfume
Super glue
Moth balls
Formaldehyde
Paint

STEM Thinking

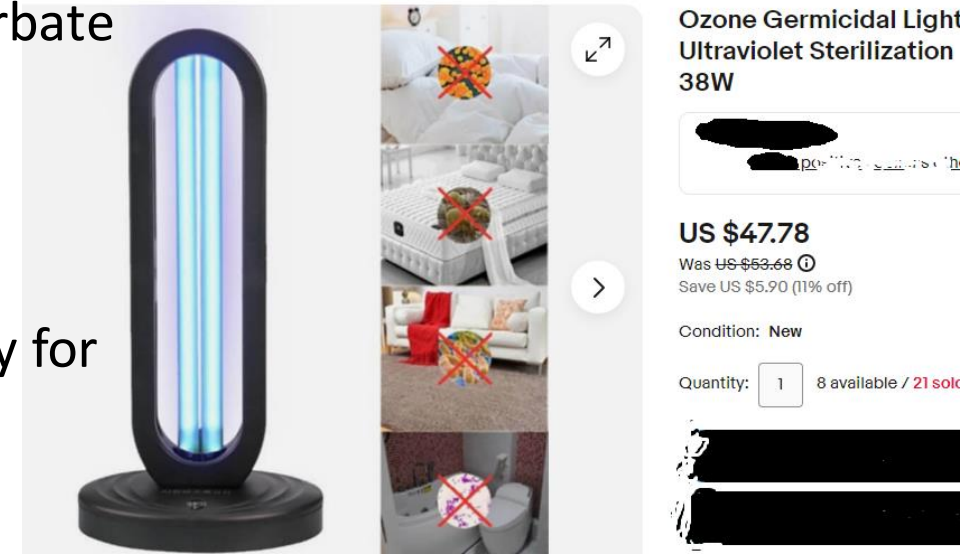ASIC 2024

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Which gases to focus on:

Highest priority focus: CO, O3, PM, RH, & T

- Long term chronic low-level CO, causes cardiovascular and brain injury, harm to fetal, children, and at-risk groups.

- O3 interactions in residence, can produce HCHO, exacerbate PM, NOx health issues, and can confound sensor measurements.
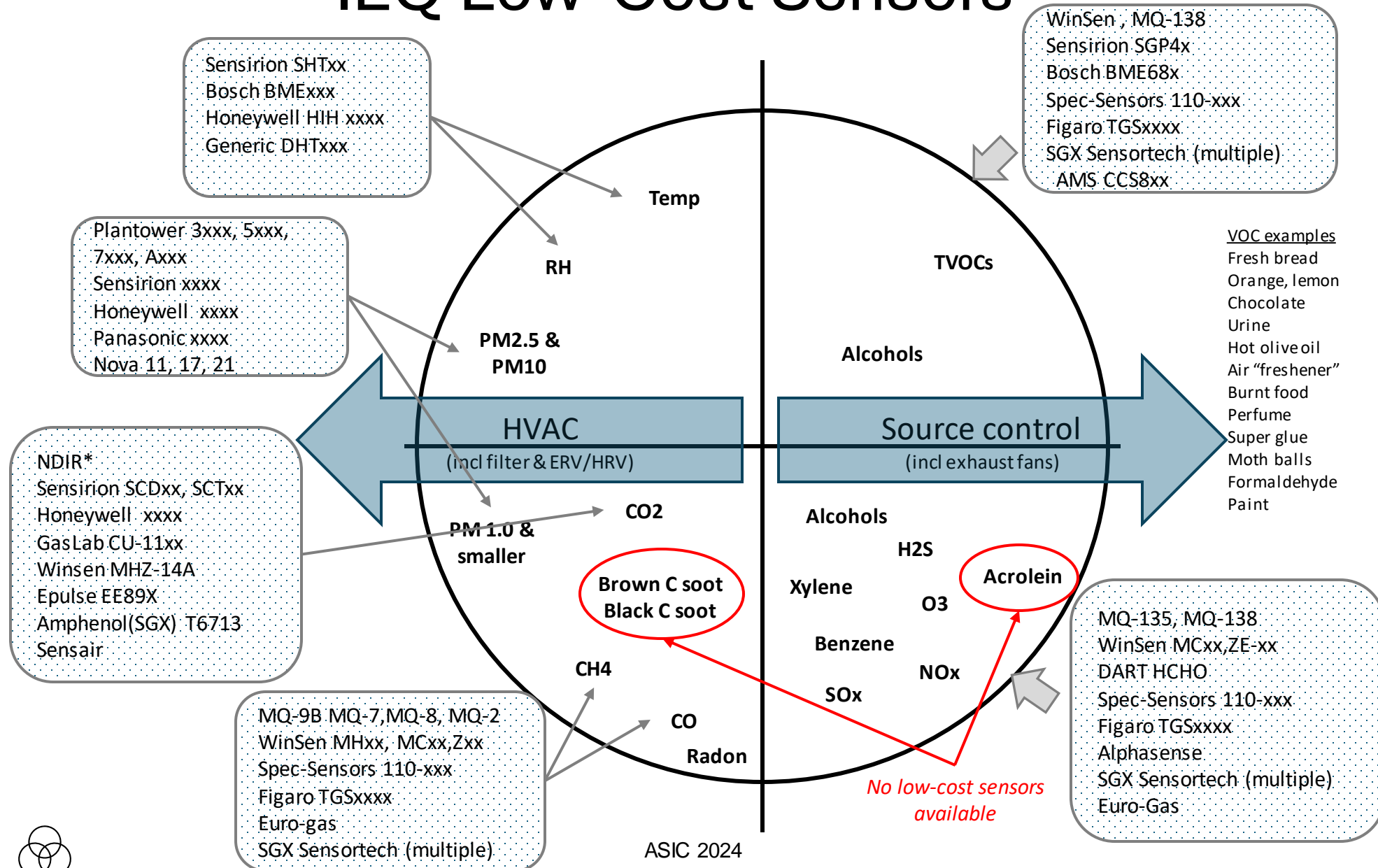
Followed by CO2, VOCs, HCHO, NOx and others

- CO2 injury requires high ppm, but is a reasonable proxy for ventilation

- Largest source of NOx is still transportation

- The list of VOCs is long, containing both good and bad

- HCHO restrictions/warnings already implemened

Ozone Germicidal Light
Ultraviolet Sterilization
38W

US $47.78
Was US $53.68
Save US $5.90 (11% off)

Condition: New

Quantity: 1   8 available / 21 sold

O3 generatior pushed as solution for IAQ and virus

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IEQ Low-Cost Sensors

Sensirion SHTxx
Bosch BMExxx
Honeywell HIH xxxx
Generic DHTxxx

WinSen , MQ-138
Sensirion SGP4x
Bosch BME68x
Spec-Sensors 110-xxx
Figaro TGSxxxx
SGX Sensortech (multiple)
AMS CCS8xx

Plantower 3xxx, 5xxx,
7xxx, Axxx
Sensirion xxxx
Honeywell xxxx
Panasonic xxxx
Nova 11, 17, 21

NDIR*
Sensirion SCDxx, SCTxx
Honeywell xxxx
GasLab CU-11xx
Winsen MHZ-14A
Epulse EE89X
Amphenol(SGX) T6713
Sensair

MQ-9B MQ-7,MQ-8, MQ-2
WinSen MHxx, MCxx,Zxx
Spec-Sensors 110-xxx
Figaro TGSxxxx
Euro-gas
SGX Sensortech (multiple)

MQ-135, MQ-138
WinSen MCxx,ZE-xx
DART HCHO
Spec-Sensors 110-xxx
Figaro TGSxxxx
Alphasense
SGX Sensortech (multiple)
Euro-Gas

Temp

RH

TVOCs

**PM2.5 &
PM10**

Alcohols

HVAC
(incl filter & ERV/HRV)

Source control
(incl exhaust fans)

VOC examples
Fresh bread
Orange, lemon
Chocolate
Urine
Hot olive oil
Air "freshener"
Burnt food
Perfume
Super glue
Moth balls
Formaldehyde
Paint

CO2

**PM 1.0 &
smaller**

Alcohols

H2S

Acrolein

Xylene

O3

**Brown C soot
Black C soot**

Benzene

CH4

NOx

SOx

CO

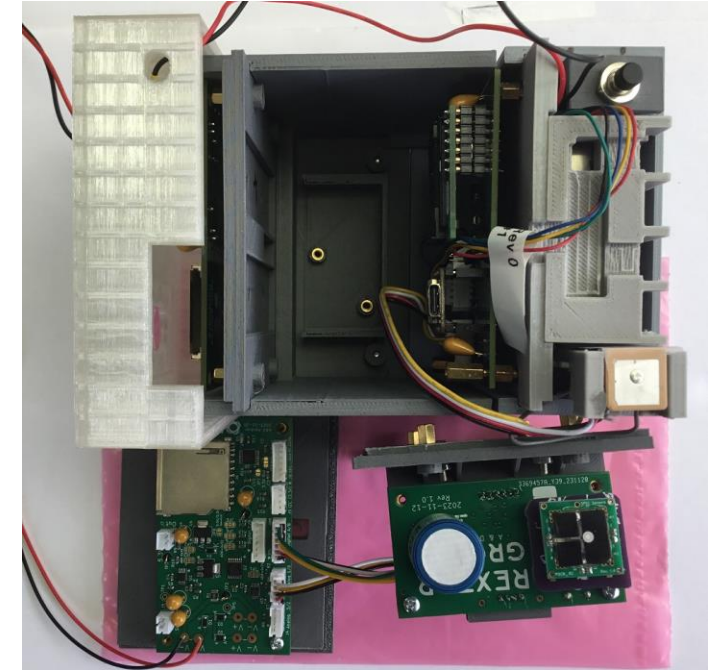**Radon**

*No low-cost sensors
available*

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STEM
Thinking

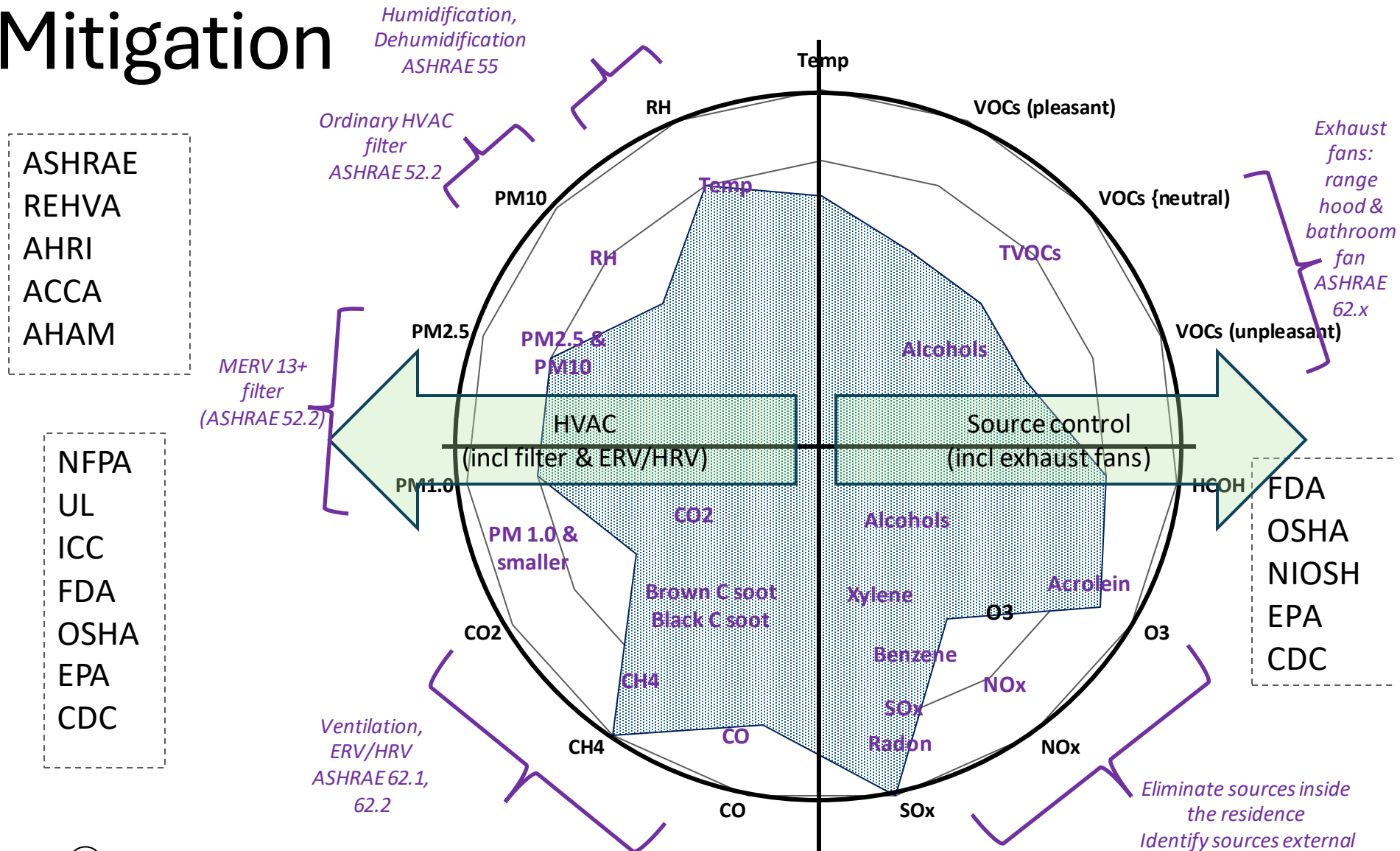# BEEHIVE Open source & Open hardware

- Multiple choices for particulate sensor
- Multiple choices for CO_2 sensor
- Multiple choices for VOC sensor
- Support for Electrochemical sensors
- GPS, SD card & WiFi

- Co-located sensors minimize effects of local T & RH, and facilitate cross-correlation between sensors.
- Compact form provides easy transportation and minimizes inconvenience to occupants.
- On-board microprocessor is done via a socketed Seed Tech XIAO or Adafruit QT Py; it's possible to use EPS32, RP2040, Nordic and SAM, by simply swapping CPU modules. Using a larger processor would allow calculation of time-weighted average values and perhaps local use of AI (e.g. TinyML).
- The software is done using Arduino IDE; the processors can be programmed in C++, or Python.

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Mitigation

ASHRAE
REHVA
AHRI
ACCA
AHAM

NFPA
UL
ICC
FDA
OSHA
EPA
CDC

FDA
OSHA
NIOSH
EPA
CDC

Humidification, Dehumidification ASHRAE 55

Ordinary HVAC filter ASHRAE 52.2

MERV 13+ filter (ASHRAE 52.2)

Ventilation, ERV/HRV ASHRAE 62.1, 62.2

Exhaust fans: range hood & bathroom fan ASHRAE 62.x

Eliminate sources inside the residence Identify sources external

HVAC (incl filter & ERV/HRV)

Source control (incl exhaust fans)

Temp
VOCs (pleasant)
RH
VOCs {neutral}
PM10
TVOCs
PM2.5
VOCs (unpleasant)
PM1.0
Alcohols
CO2
HCOH
Alcohols
Xylene
Acrolein
Brown C soot
Black C soot
O3
CH4
Benzene
CO
SOx
Radon
NOx
CH4
CO
SOx
NOx
O3

Radon mitigation handled separately

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Our Target – Avoid the Bullseye

In the game of darts, bullseye is good.

In our chart – a bullseye is illness or even death.

Think of a child's throat narrowing because of adverse reaction to chemicals.

We want to expand as many points into the outer most ring as possible.

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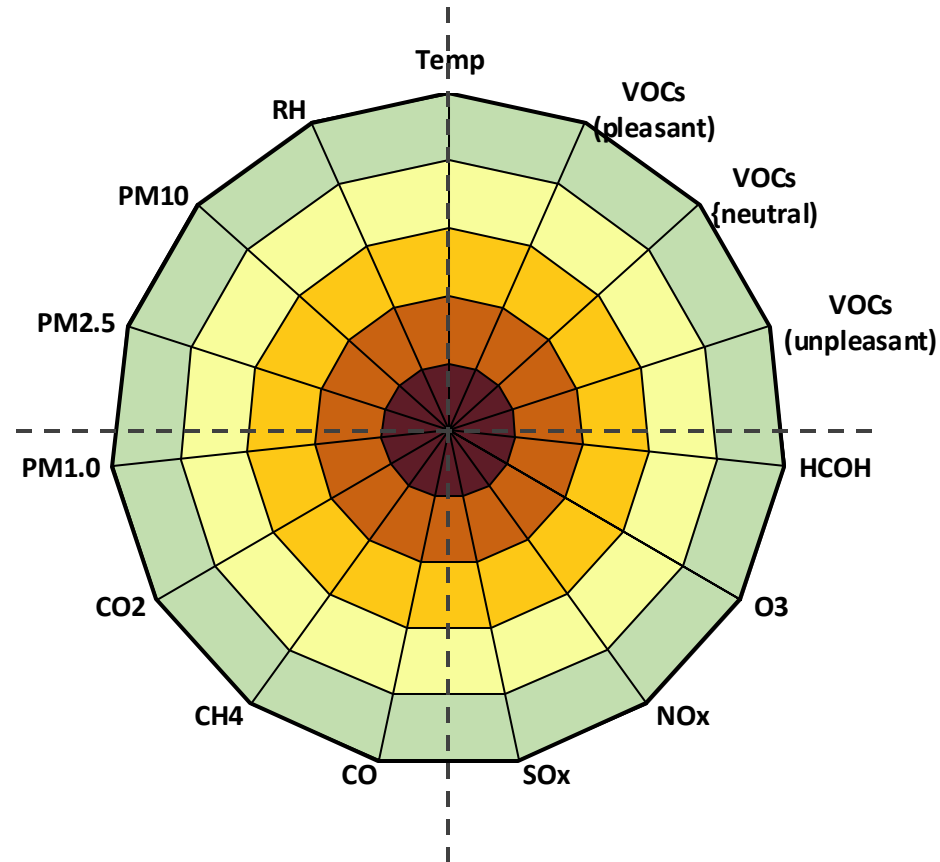
What we could measure*

Outer circle = "perfect"

Center point = "terrible"
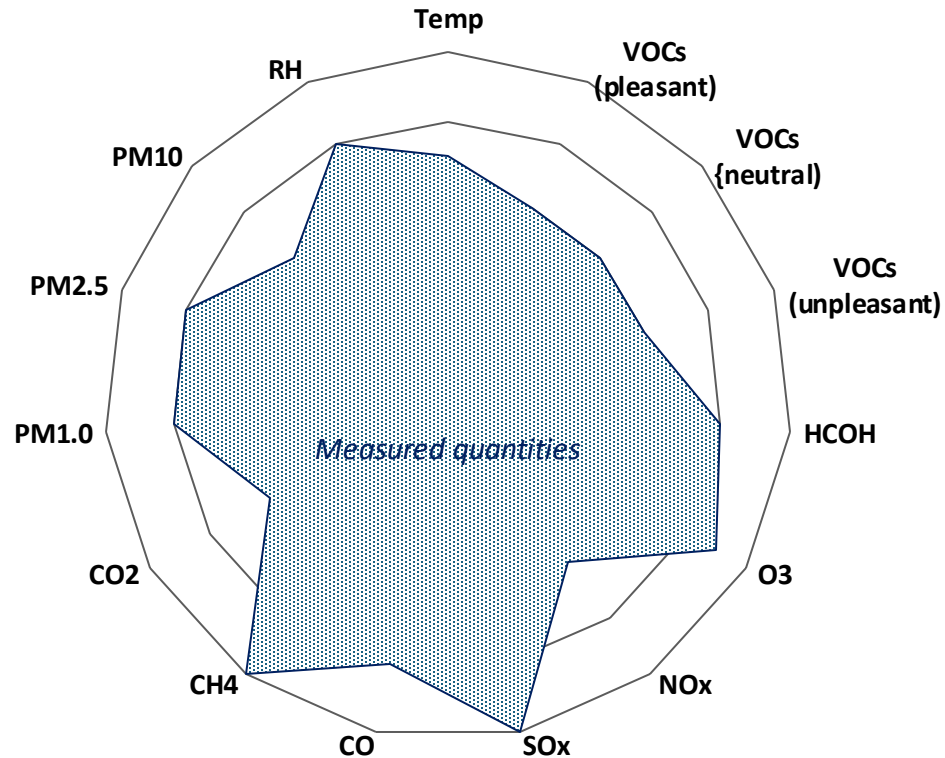
- *Not real data*

We focus on devices that have flexibility for measuring inside building and outside building gases and environmental conditions with just basic addition or changing of a few sensors.

* Lots of low cost sensors available. Instrument is a work in progress with students. We adapt.

STEM Thinking

Mapping Temp Measurements to Radar Chart

Simple stop light colors

Each variable has its own mapping rules.

STEM Thinking
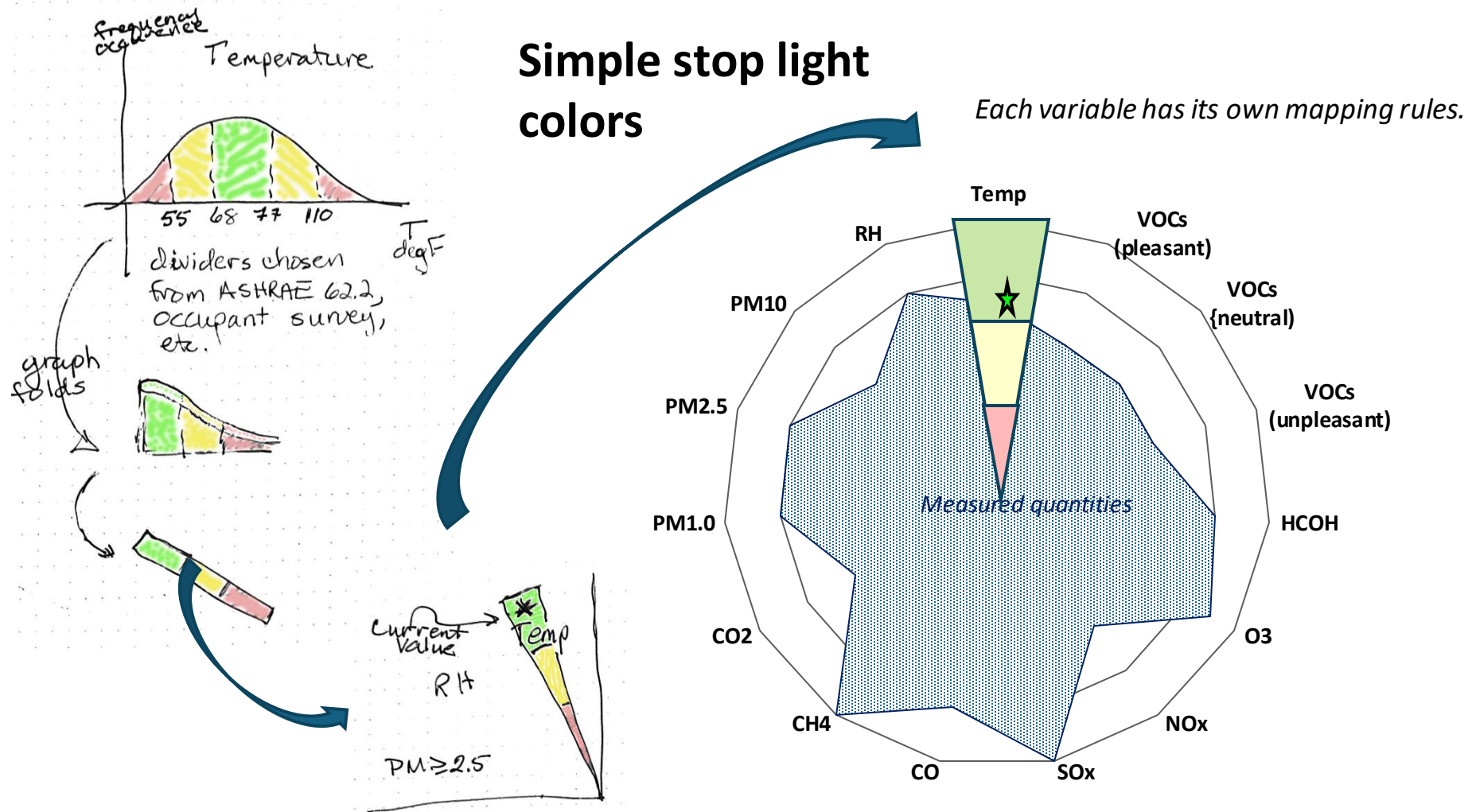
Recognizing the pattern

Mitigation of IAQ requires identifying patterns, for which AI / ML excels.

The training object doesn't need to be humanly recognizable, just transformed consistently.
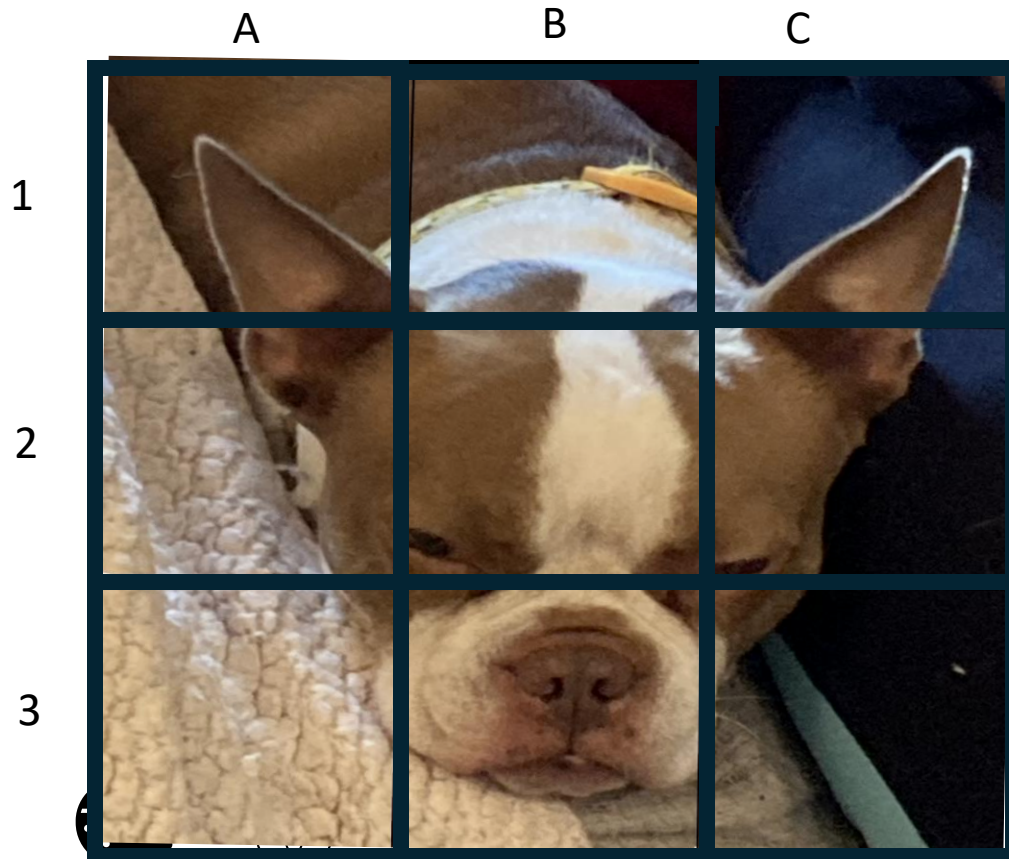
1A -> 3A
1B -> 1A (-90)
1C -> 2C(180)

2A->2B
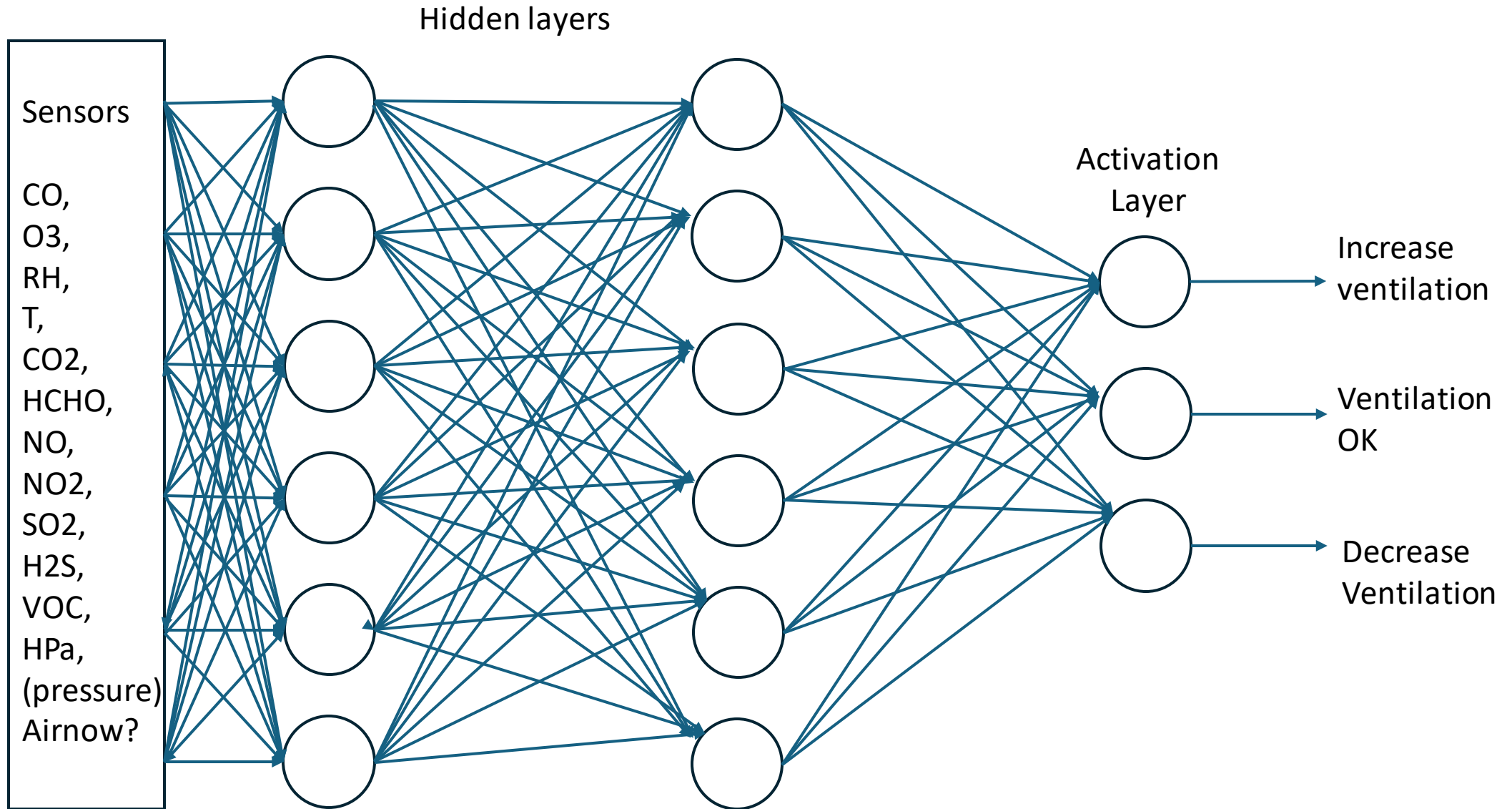2B-> 1B
2C -> 2A

3A -> 1C
3B -> 3C(180)
3C -> 3B

Thinking
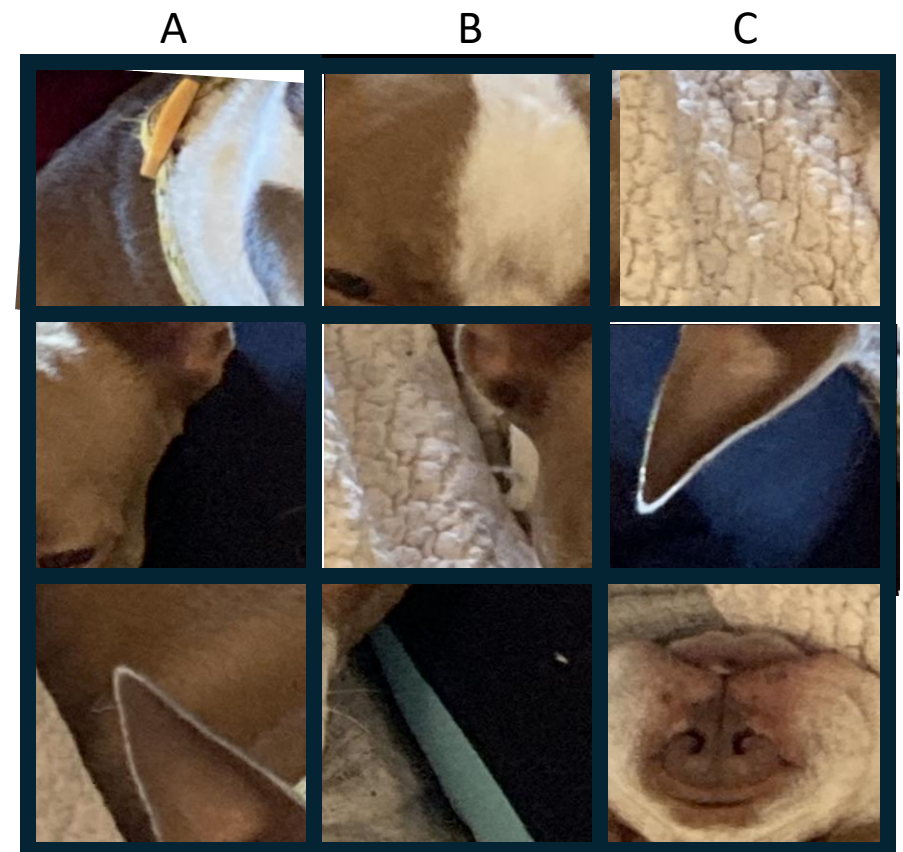
Map sensor values to color designated cell to create data

CO	O3	RH	T
PM1.0	PM2.5	PM5.0	PM10
CO2	TVOC	VOC_INDX	NOX_INDX
NO2	HCHO	Particulates (Airnow)	Other values (Airnow)

Color mapping is a means to "normalize" the data.

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Generalized Neural Network

Hidden layers

Activation Layer

Sensors

CO,
O3,
RH,
T,
CO2,
HCHO,
NO,
NO2,
SO2,
H2S,
VOC,
HPa,
(pressure)
Airnow?

Increase ventilation

Ventilation OK

Decrease Ventilation

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IAQ residential datasets are sparse when compared to datasets for outdoor air

Possible public sources for IAQ training datasets:

- UC Irvine (https://archive.ics.uci.edu/)

- DRYAD   (https://datadryad.org/stash/dataset/doi:10.7941/D1ZS7X)

- Kaggle   (https://www.kaggle.com/datasets)

- IEEE Dataport (https://ieee-dataport.org/)

- Mendeley Data (https://data.mendeley.com/)

- DANS-EASY (https://easy.dans.knaw.nl/ui/home)

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Data needs context

- Even data from the same instrument varies with location, temperature, sensor age, etc.
- Now try using datasets from multiple sources!

Negative ppm?

Real or anomalous?

Different times and time scales
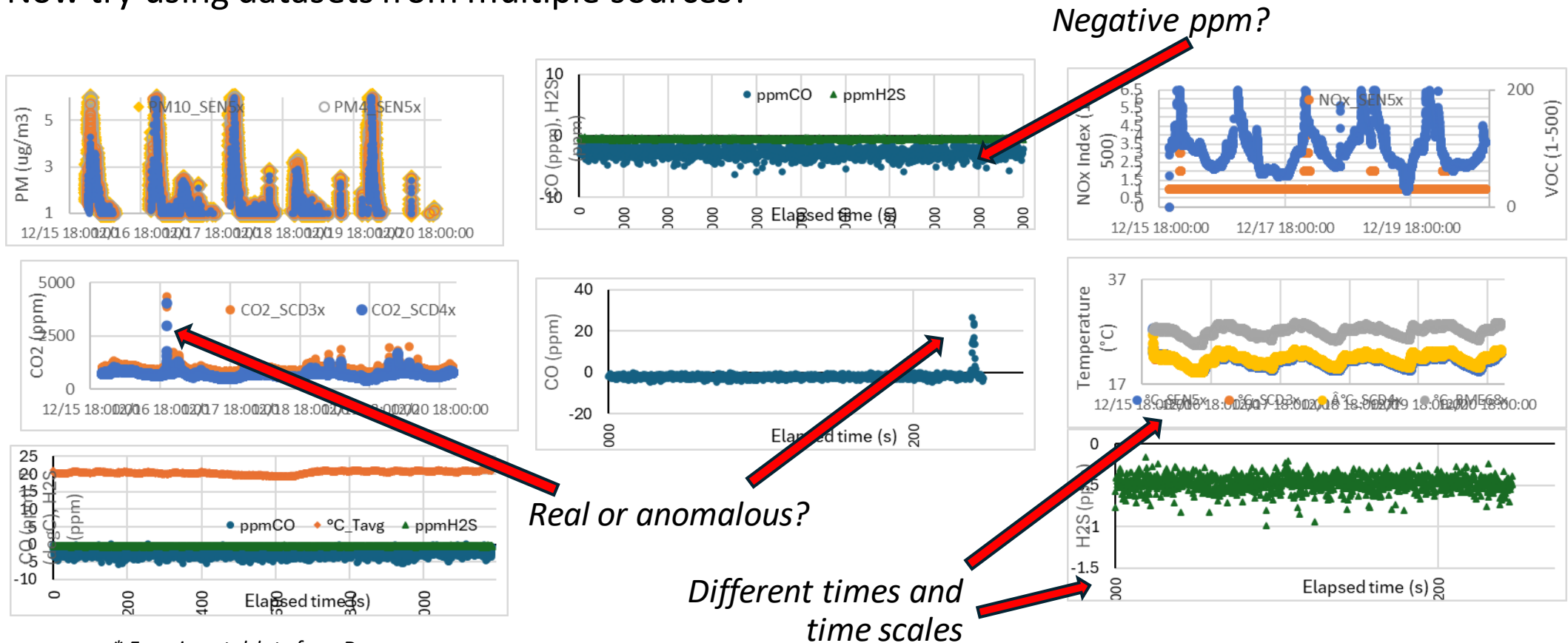
* Experimental data from D Heidner 2023-2024

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Ensure Curated & Labeled Data

Labeled data that clearly identifies dogs and non-dogs. (good/bad)

- Data for the gases of concern

- Measured values and time weighted values

- Provenance of the curated data is needed – if you're not a dog expert

- Scaling, accuracy, calibration, sensor choices

- Dataset to sufficient to represent diverse residential spaces

- Enough samples enough to train, different samples to test/verify

STEM Thinking

Labelled and Annotated Data is a problem!

Because IAQ includes occupant perception, we need:

- to aid the curation process by "bookmarking" as the data is collected – events smells, irritation etc.

- to "bookmark" possible health effects such as allergy, wheezing, asthma

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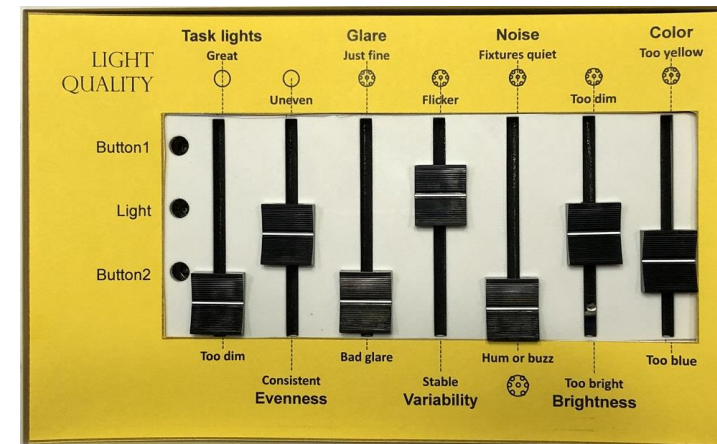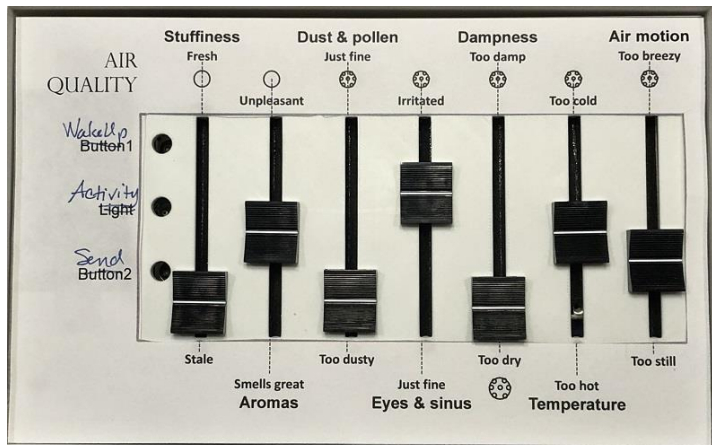
Other issues related to IAQ home sensors

- Guidelines for IAQ sensor placement in residence

- Identify/verify sensor technologies which are appropriate

- Sample intervals, one minute, one hour?

- Autocal? Some CO2 sensors autocal using indoor air

- Students seldom have access to "zero air calibration gas"

- Some sensors have ambiguous span, accuracy, sensitivity, resolution, cross sensitivity data – beyond most high school and undergraduate's ability to properly handle.

Summary.

- Ventilation and air filtration require energy; if we can reduce the air flow WHILE maintaining good IAQ we can reduce energy.

- Conversely, if residential occupancy activity increases ML & IAQ would allow us to increase the ventilation and filter as needed automatically.

- A "radar" like IAQ chart helps to inform and explain to the residents why the mechanical ventilation is running – perhaps at high volumes.

- Data collected with the "bookmarks" could help better narrow down the health impacts from the IAQ.

STEM Thinking

Questions?

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We are happy to communicate with teachers and other educators. We do not communicate with students in grades 12 and below.

For GitHub and other queries, find us at ASIC, message via LinkedIn or Whova, or visit poster B07.

The Rextor Group, Kirkland, WA

REXTOR GROUP

The Legalities

This presentation was first presented at ASIC 2024, Riverside, CA.

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