Aerosols, ventilation and the environment: competing agonist-antagonists

The competing pressures of comfort, air quality, airborne transmission and climate change

Stuart Dalziel

Department of Applied Mathematics and Theoretical Physics
University of Cambridge

The problem: we are affected by what we breathe

UNIVERSITY OF CAMBRIDGE

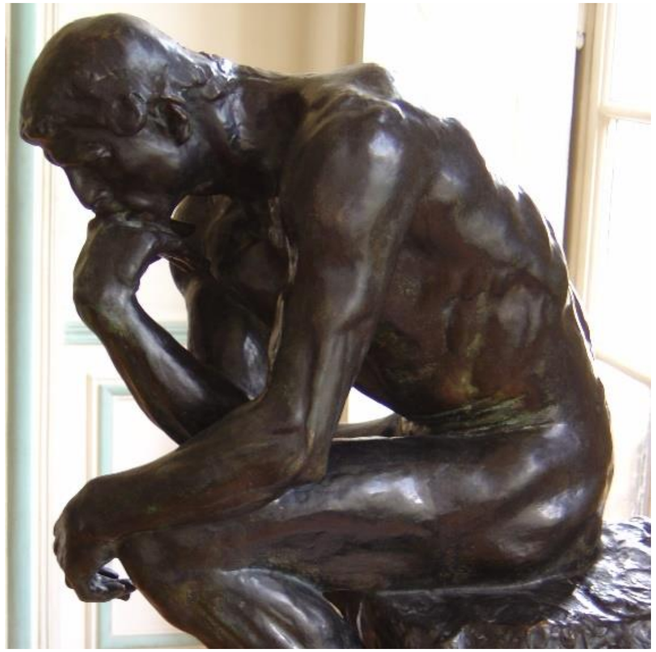
Breathing in

- O_2

  …
- CO_2
- CO
- VOC
- O_3

  …
- Aerosols

?



Breathing out

- CO_2
- Water vapour
- Heat
- Droplets/aerosols

  …
- Pathogens

Impacts

- Alertness
- Comfort
- Health
- Illness

Influenced by

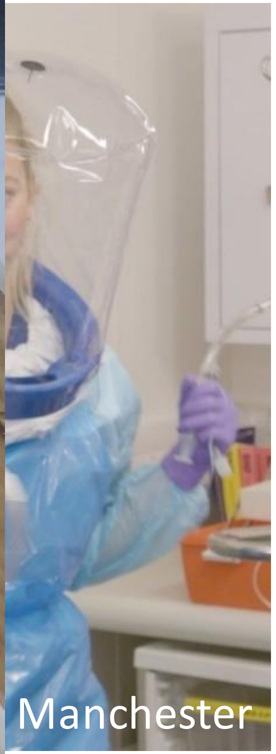
- Vocalisations
- Activity
- Environment
- Health

Extreme solution

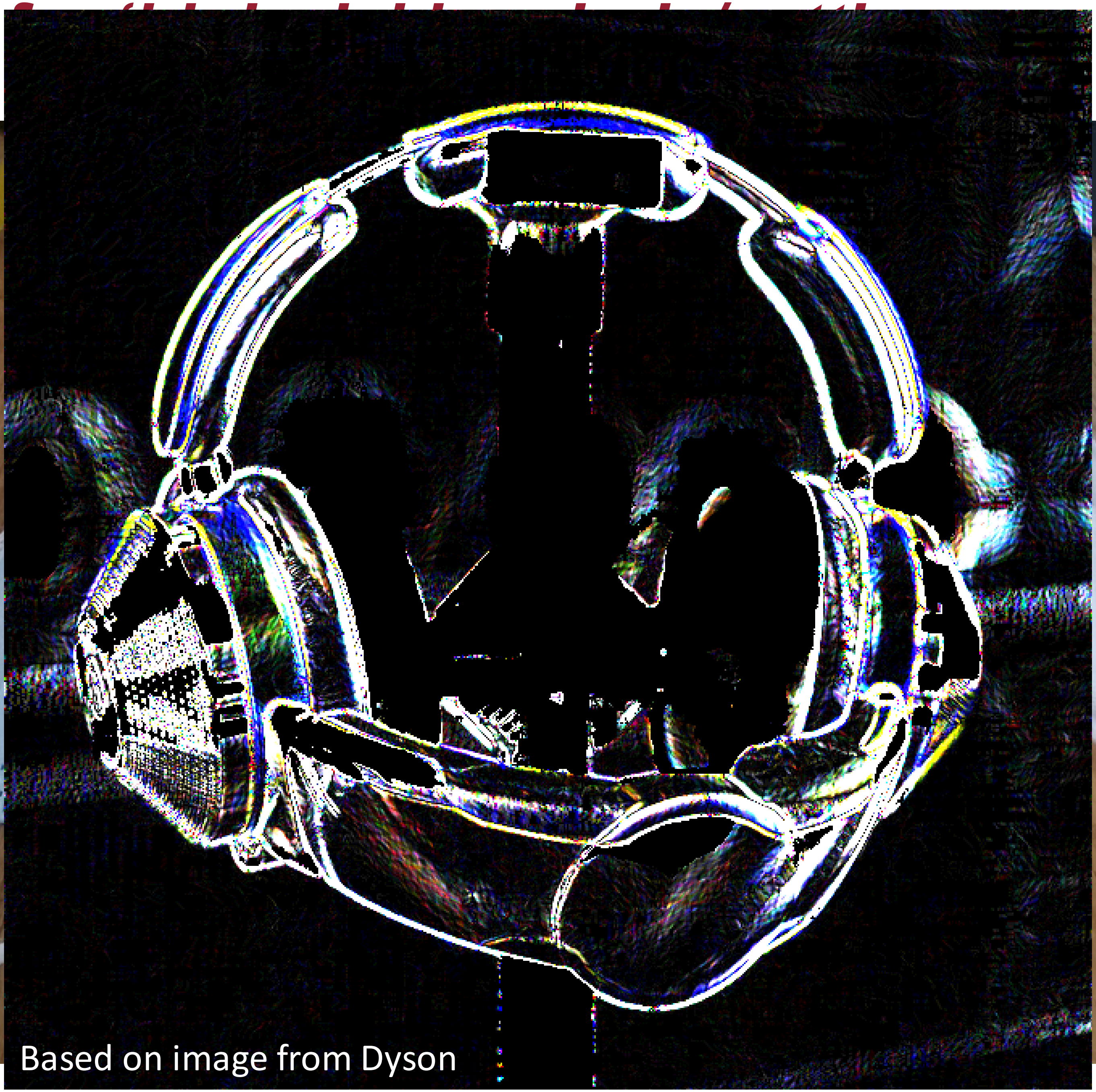
PPE for 'high-risk' settings

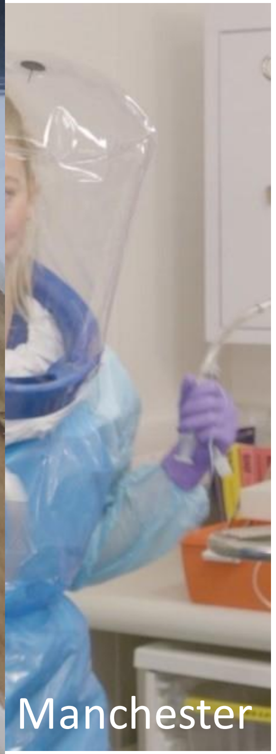
PPE for 'medium-risk' periods/settings

UNIVERSITY OF CAMBRIDGE



Masks – ppe





‘Simple’ masks – what do they do?

UNIVERSITY OF CAMBRIDGE

Droplets

- Might be infectious
- Large droplets: ballistic; may settle (fomites?)
- Droplets evaporate
  - → concentrate infection
  - → less affected by gravity → aerosol?
- Aerosols
  - → transmission with separation (space/time)

Masks

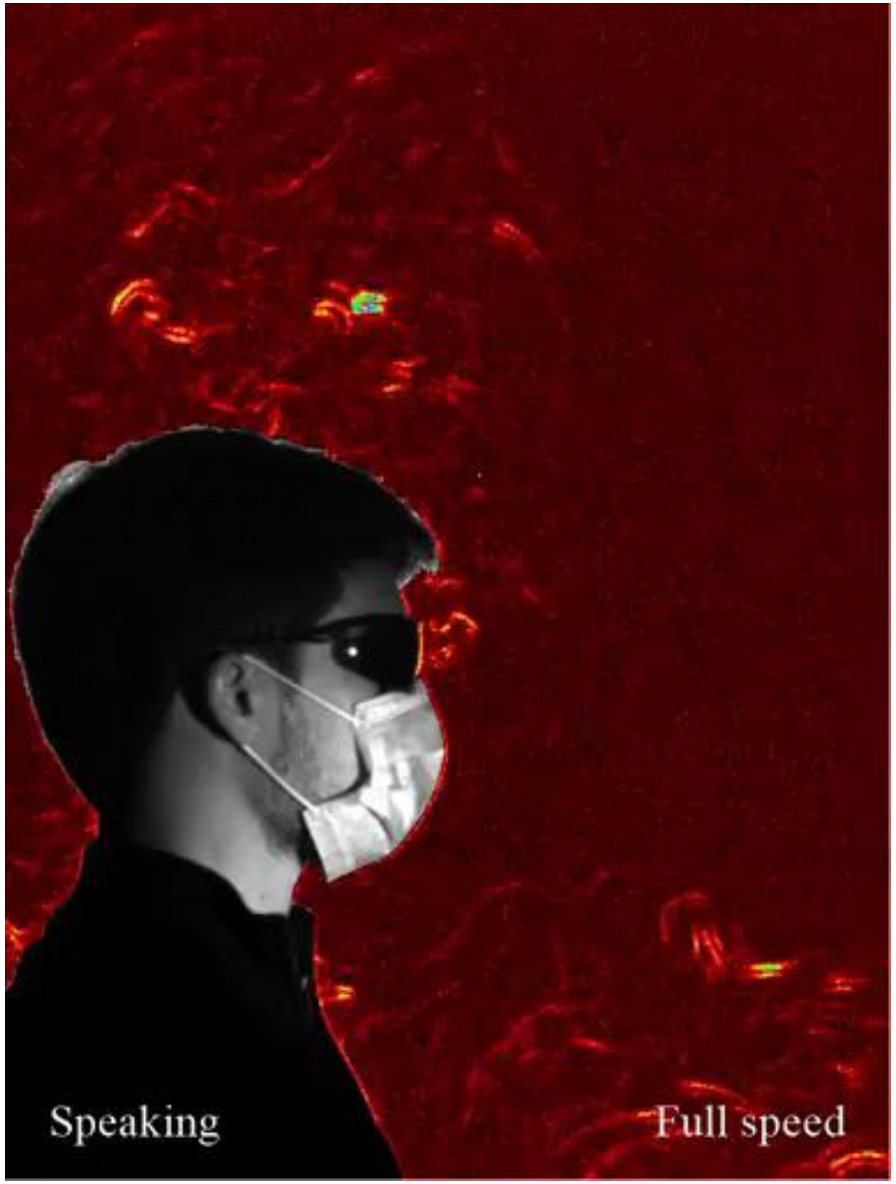
- Redirect
  - Away from others
  - Into *body plume’*
- Filter
  - Depends on fit and type
  - Not all air passes through
- Capture
  - Droplets do not quite follow the air

But

- Respiration challenges
- Comfort
- Communication
- Eating
- Vision impairment (e.g. fogging)
- Perceived risk
- Self-image
- Compliance
- …

Body heat and speaking

UNIVERSITY OF CAMBRIDGE



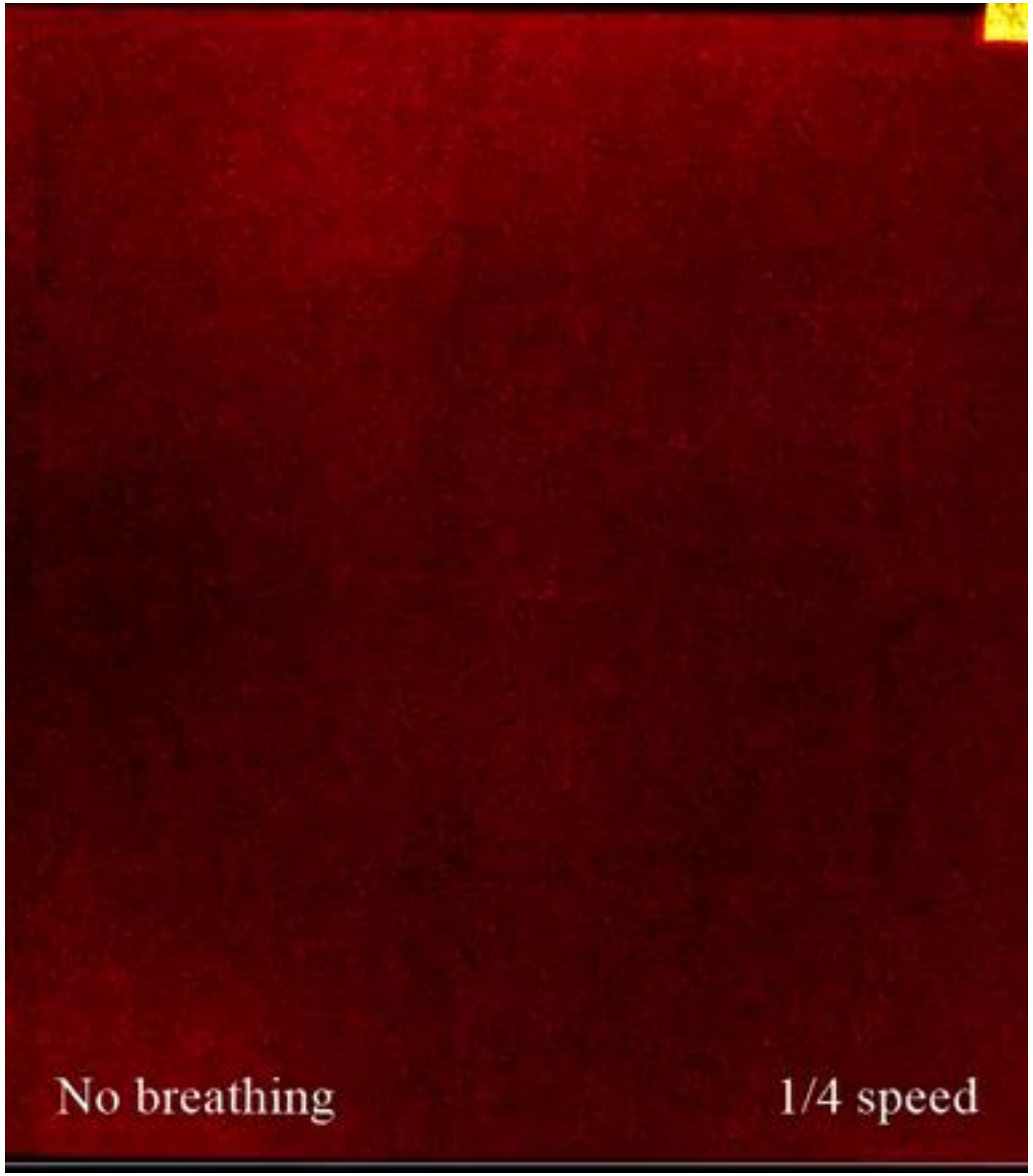
Some behaviours more risky

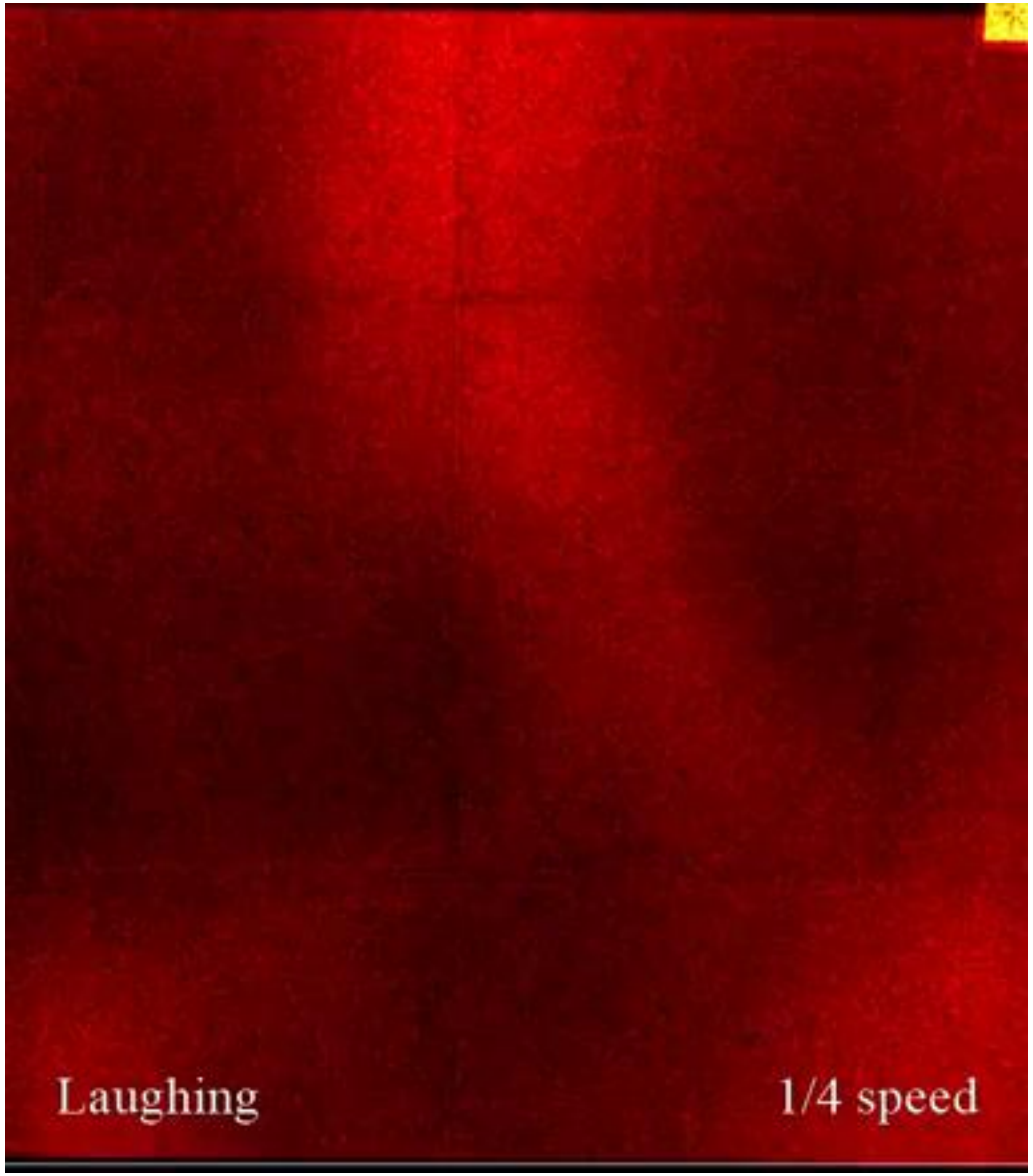
UNIVERSITY OF CAMBRIDGE

Should pantomime be banned?

Not necessarily stationary

UNIVERSITY OF CAMBRIDGE

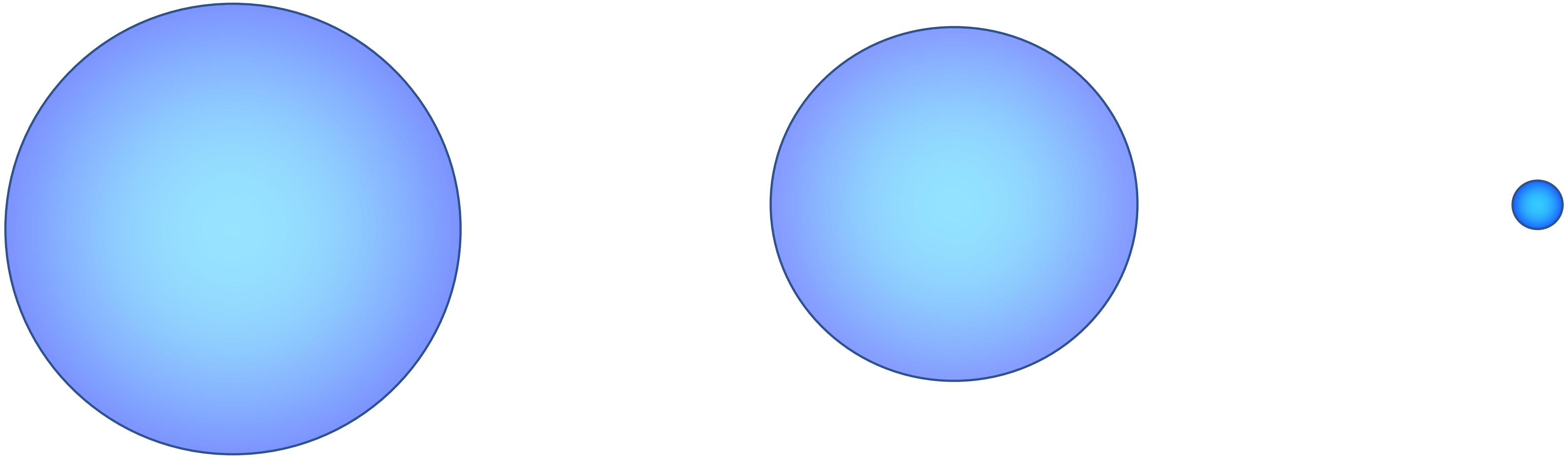




Need more than a sticking plaster

UNIVERSITY OF CAMBRIDGE

Droplets/aerosols



Well-mixed isolated rooms

Simple

- Only sources within space

$$V\frac{d}{dt}C = \sum_{i=1}^{n_T} c_i q_i + (C_0 - C)Q_F$$

$$C \to C_0 + \frac{1}{Q_F}\sum_{i=1}^{n_T} c_i q_i$$

What is acceptable?
What are the quanta?

- Wells-Riley

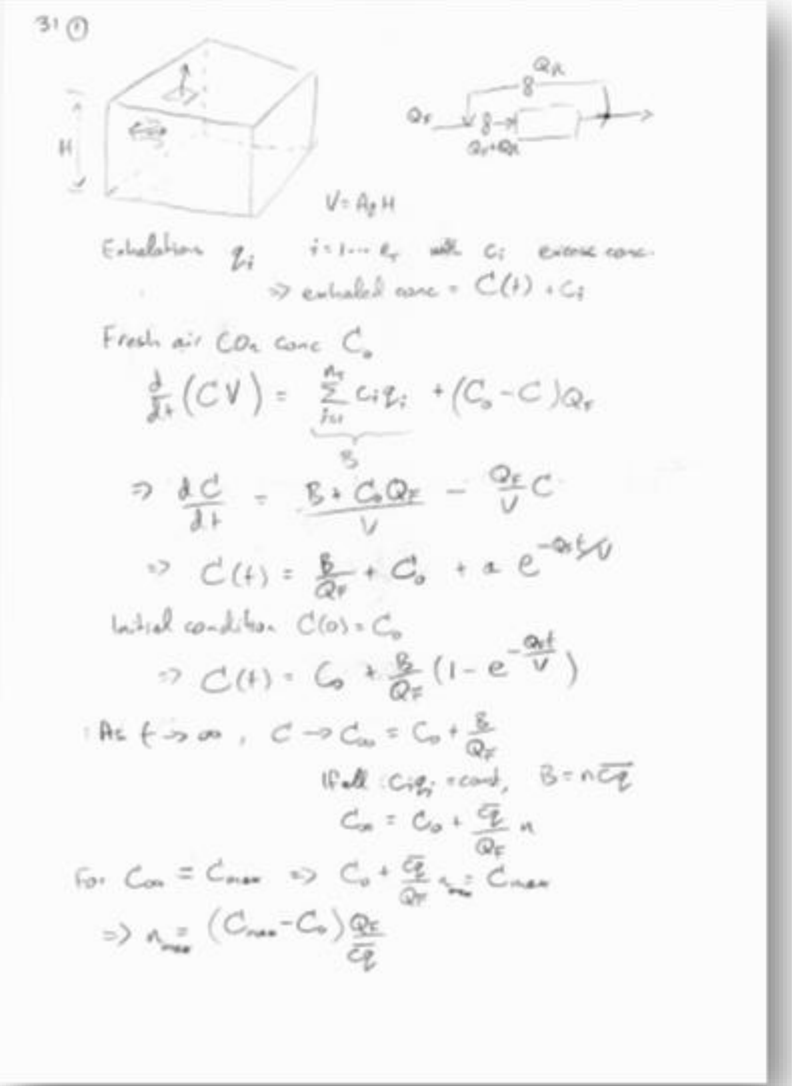
$$P \propto 1 - \exp\left(-\int_0^{t_s} \Gamma\, dt\right)$$

$$V\frac{d}{dt}\Gamma = \sum_{i=1}^{n_T} \gamma_i q_i + (\Gamma_0 - \Gamma)Q_F$$

But…

- Are rooms well mixed?
  - ➢ Distribution of sources?
  - ➢ Airflows from ventilation system?
  - ➢ Stratification within the room?
- Are rooms isolated?
  - ➢ What are the fluxes *between* spaces?

How can we tell?



31 ①

Q_R

Q_F

$Q_F + Q_R$

H

$V = A_f H$

Exhalation q_i $i = 1 \cdots n_T$ with c_i excess conc.

$\Rightarrow$ exhaled conc $= C(t) + c_i$

Fresh air CO_2 conc C_0

$$\frac{d}{dt}(CV) = \underbrace{\sum_{i=1}^{n_T} c_i q_i}_{B} + (C_0 - C)Q_F$$

$$\Rightarrow \frac{dC}{dt} = \frac{B + C_0 Q_F}{V} - \frac{Q_F}{V}C$$

$$\Rightarrow C(t) = \frac{B}{Q_F} + C_0 + a e^{-Q_F t/V}$$

Initial condition $C(0) = C_0$

$$\Rightarrow C(t) = C_0 + \frac{B}{Q_F}\left(1 - e^{-\frac{Q_F t}{V}}\right)$$

At $t \to \infty$, $C \to C_\infty = C_0 + \frac{B}{Q_F}$

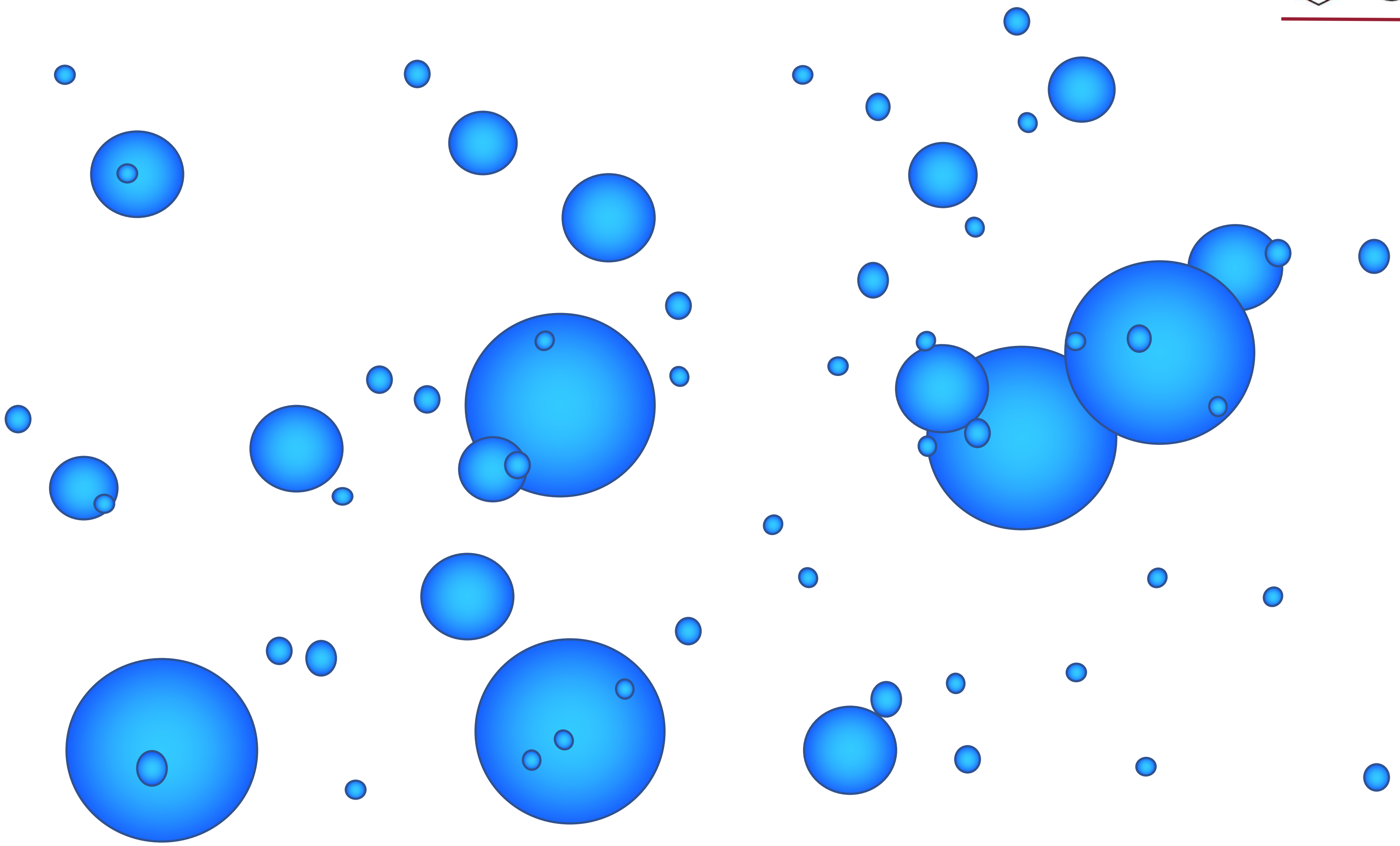
If all $c_i q_i$ = const, $B = n\overline{cq}$

$$C_\infty = C_0 + \frac{\overline{cq}}{Q_F} n$$

For $C_\infty = C_{max} \Rightarrow C_0 + \frac{\overline{cq}}{Q_F} n_{max} = C_{max}$

$$\Rightarrow n_{max} = (C_{max} - C_0)\frac{Q_F}{\overline{cq}}$$

Proxies – droplets/aerosols

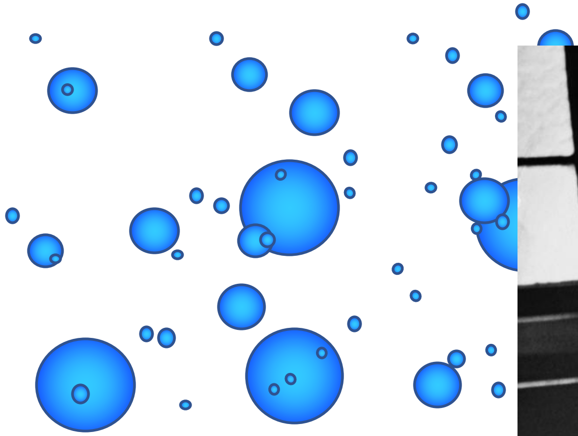


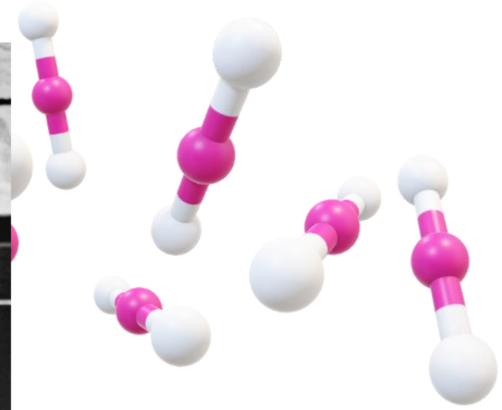
- ✗ Hard to measure *in situ*
- ? What is problematic?

Proxies – CO_2

- ✓ Existing technology
- ✗ Not visible
- ✗ Point measurements
- ✗ *Not* aerosol

Proxies – smoke

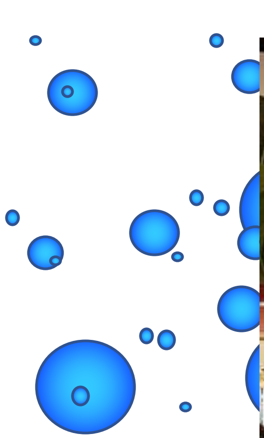




Hulton-Deutsch Collection

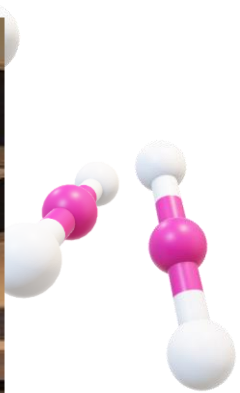
- ✗ Health issues
- ✗ Need to be old enough to remember

Proxies



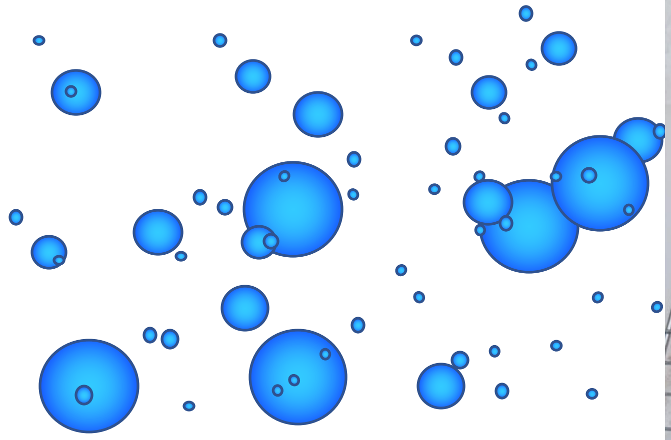
Hulton-Deutsch Collection

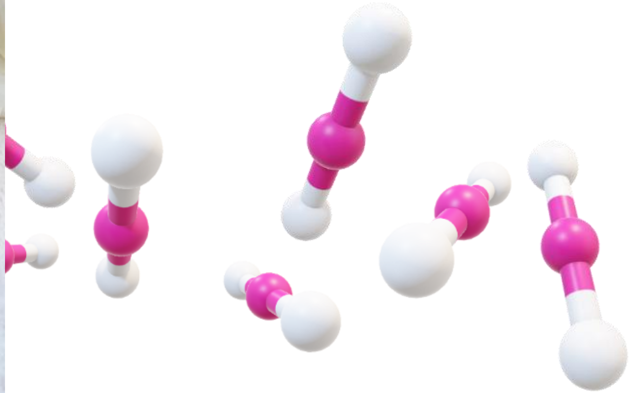
BBC

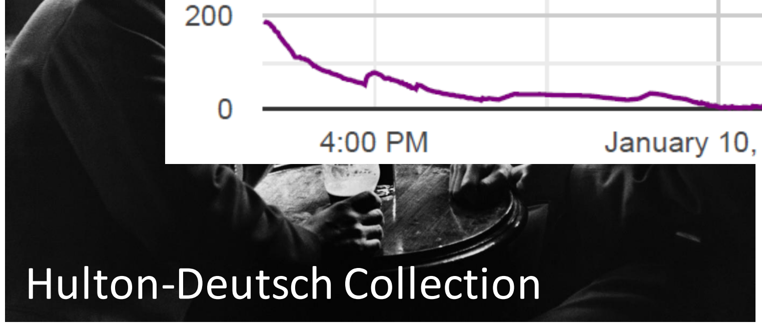


- Olfactory response extremely nonlinear

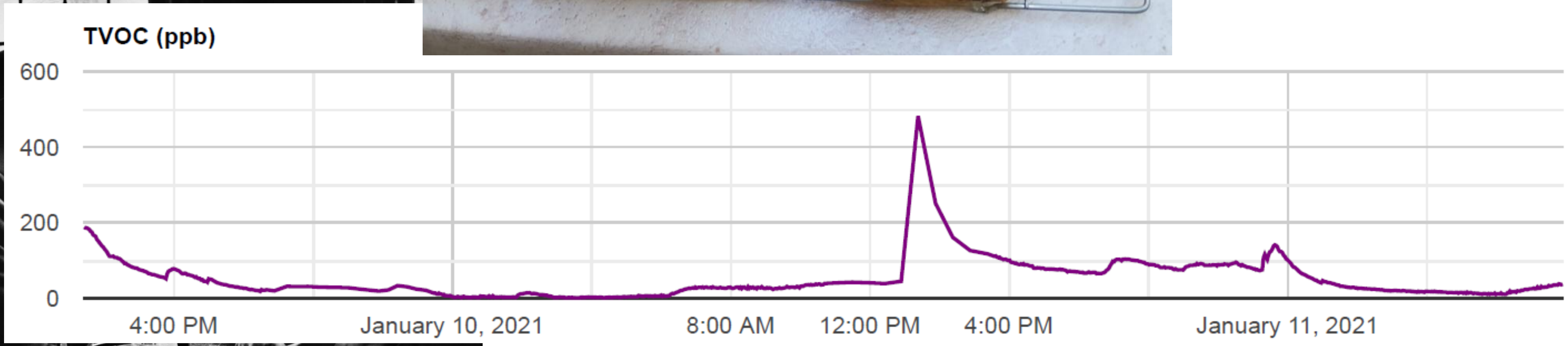
Proxies





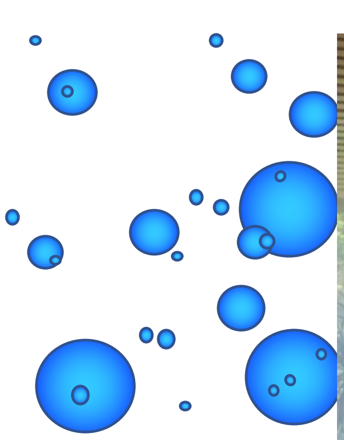


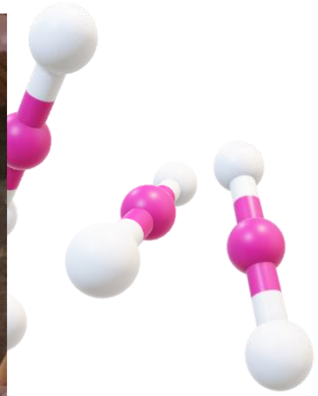
Hulton-Deutsch Collection



- ✓ Cheap technology
- ✗ Many sources of VOC

Proxies

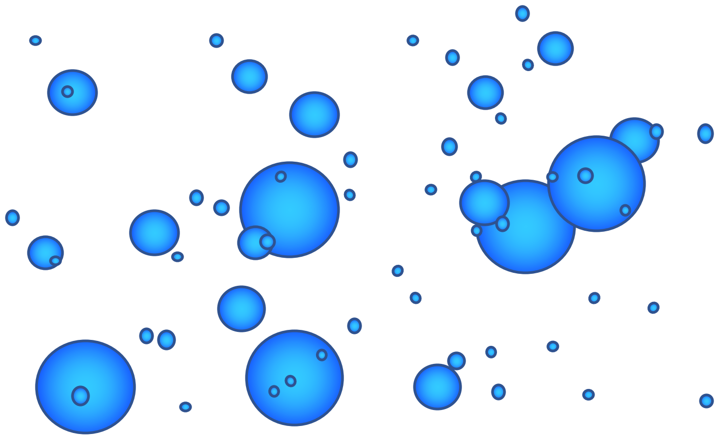


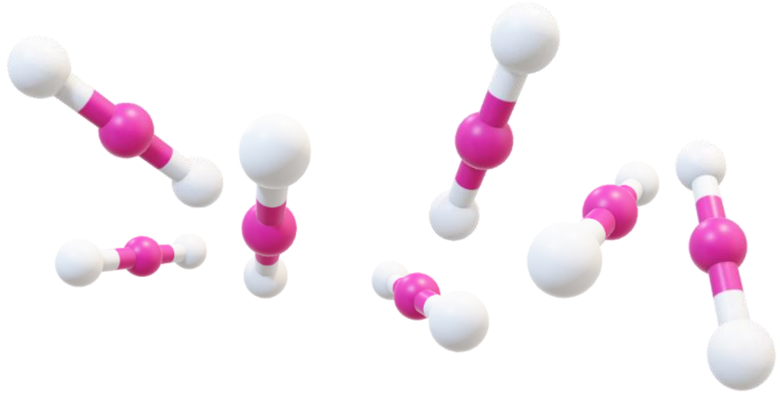


Hulton-Deutsch Collection

Proxies

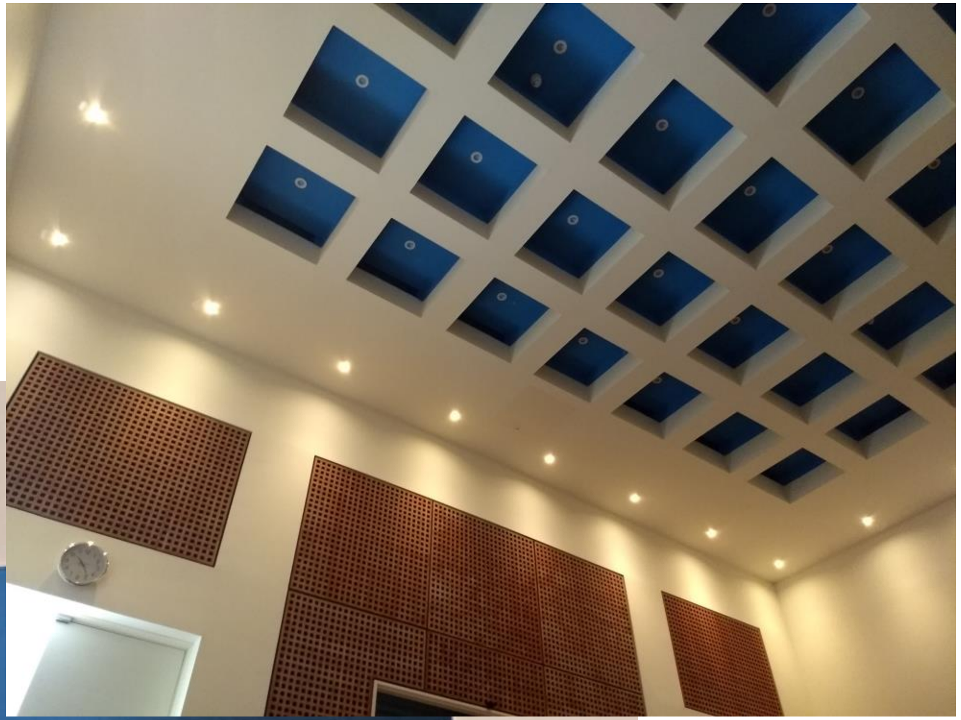
UNIVERSITY OF CAMBRIDGE

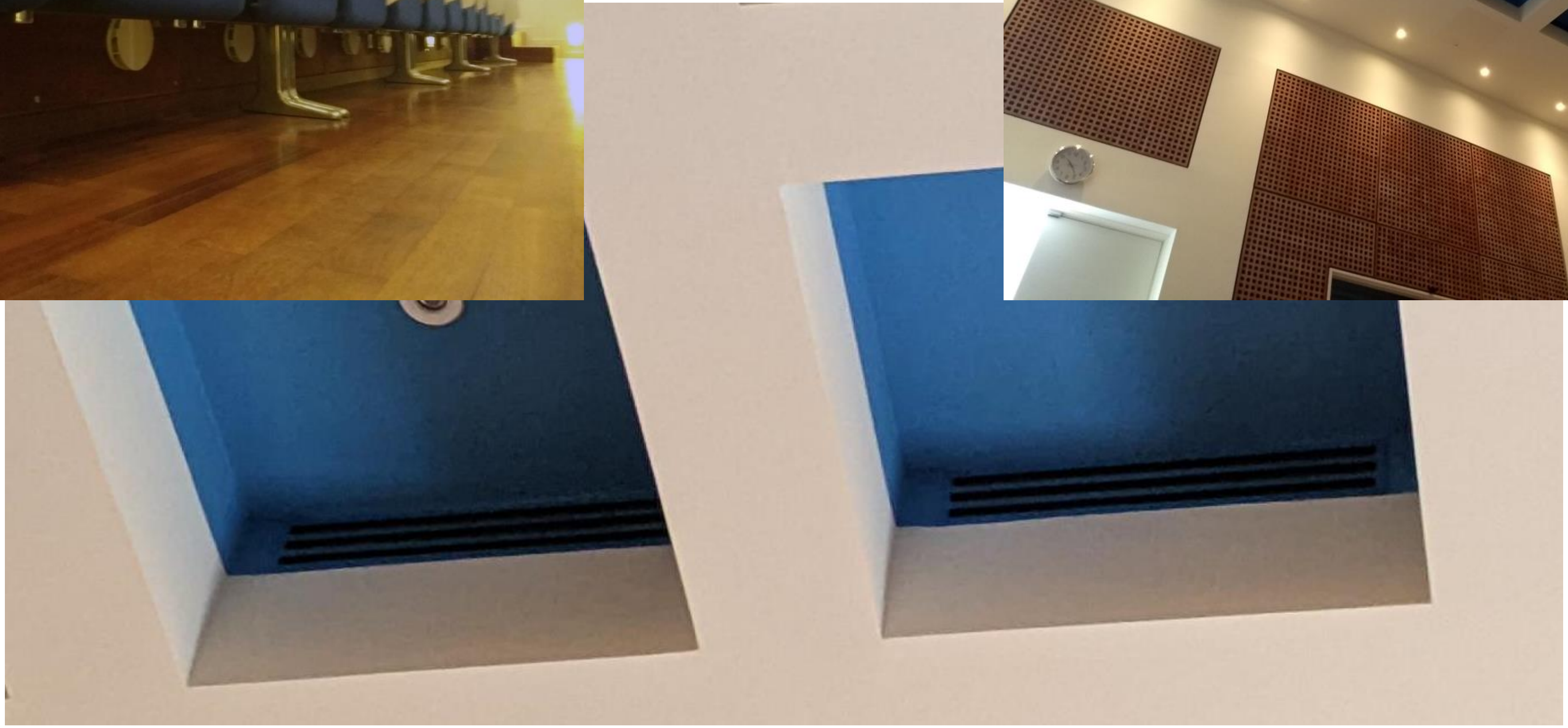




This room

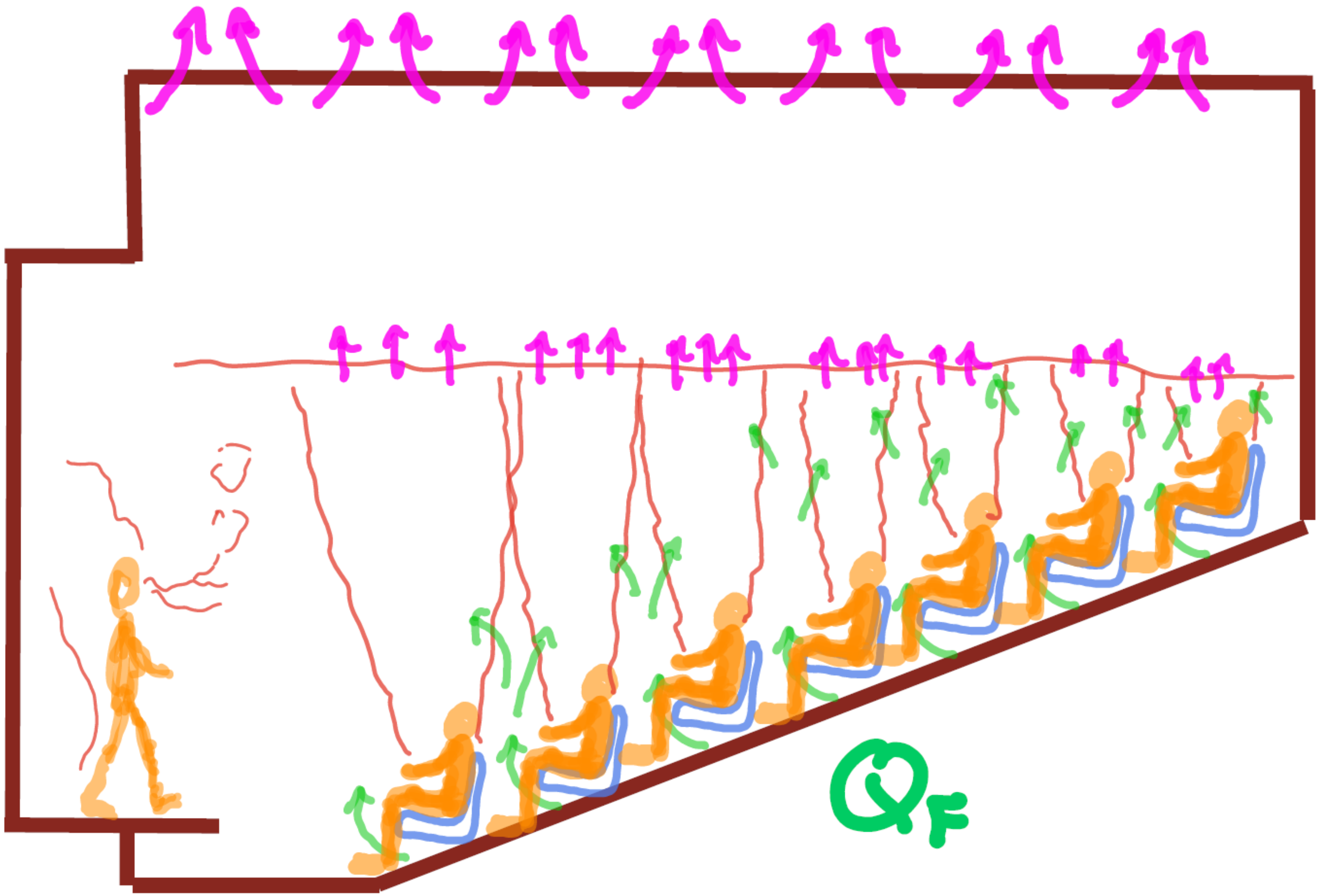
UNIVERSITY OF CAMBRIDGE



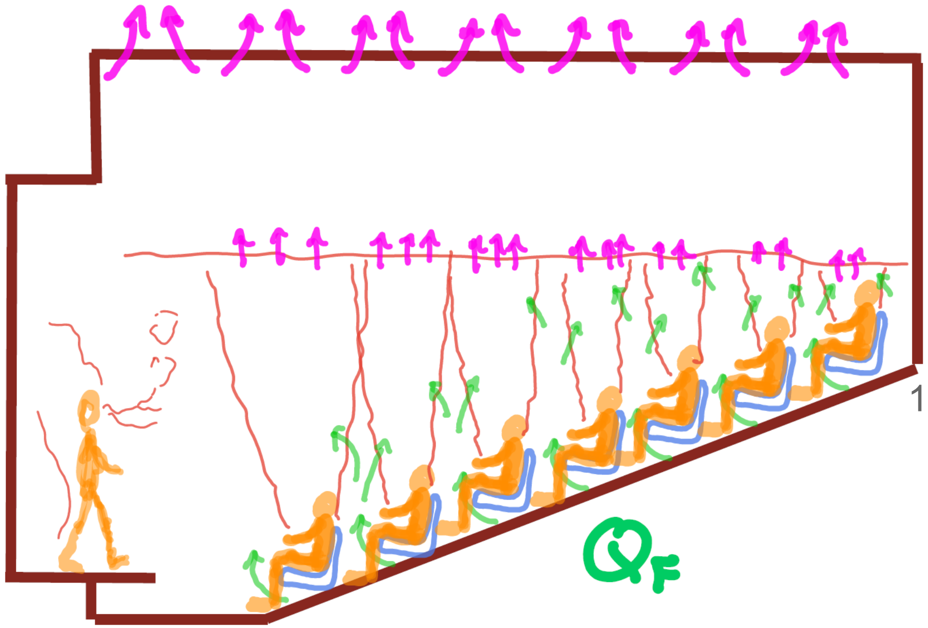


This room – displacement ventilation

UNIVERSITY OF CAMBRIDGE



This room – displacement ventilation



$$Q_F = \sum_{i=1}^{n_A} \gamma F_0^{2/3} (h - z_i)^{5/3}$$

$$\approx \int_0^L \frac{n_A \gamma F_0^{2/3}}{L} (h - sx)^{5/3}\, dx$$

$$= \frac{3 n_A}{8 s L} \gamma F_0^{2/3} \left[h^{8/3} - (h - sL)^{8/3} \right]$$

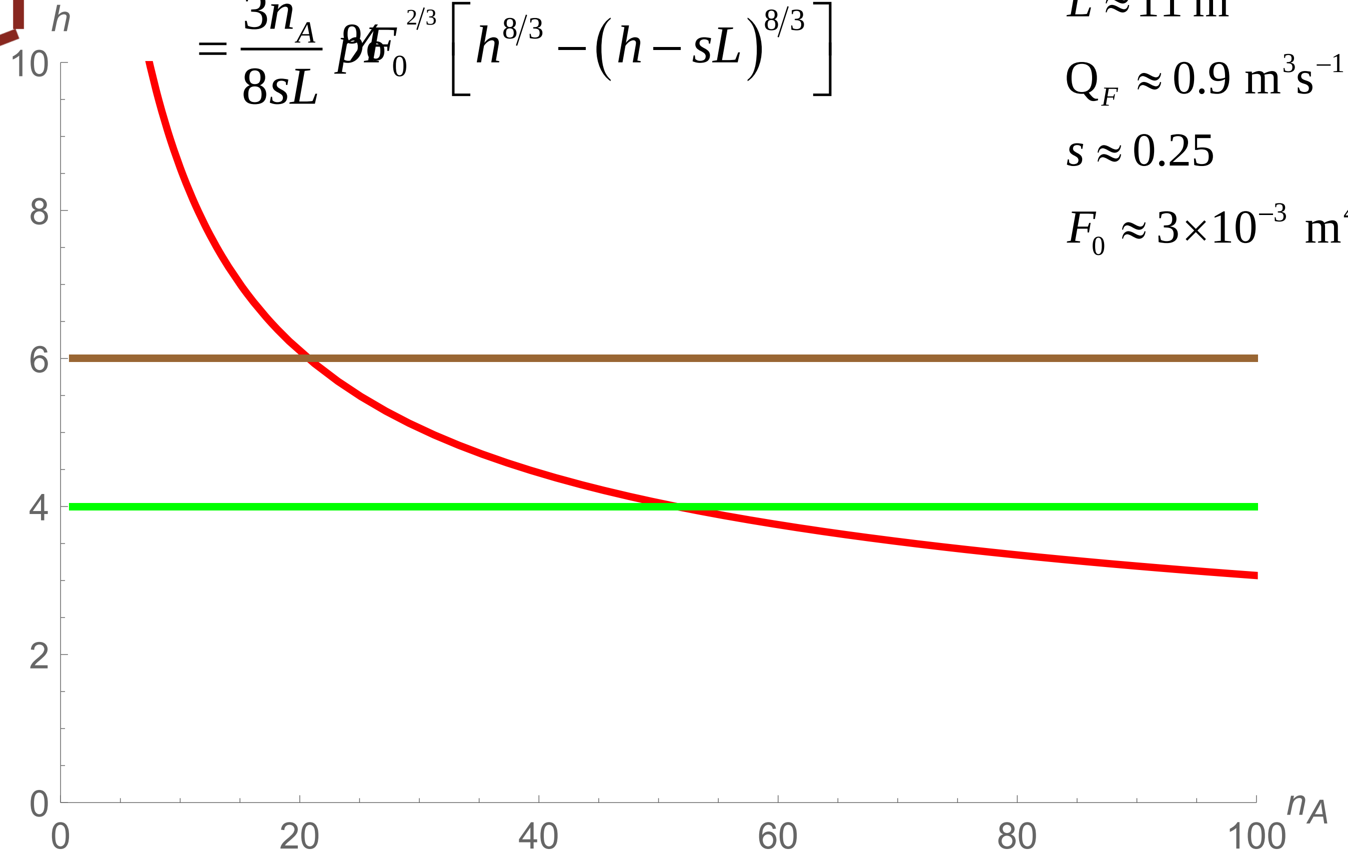
$$\gamma = \frac{6\alpha}{5} \left(\frac{9\alpha}{10} \right)^{1/3} \pi^{2/3} \approx 0.16$$

$L \approx 11$ m

$Q_F \approx 0.9\ \mathrm{m^3 s^{-1}}$

$s \approx 0.25$

$F_0 \approx 3 \times 10^{-3}\ \mathrm{m^4 s^{-3}}$



Many assumptions

- Masks
- Virtual origin on floor
- Unaffected by furniture and neighbours
- Fresh air distribution
- First-front horizontal

This room – displacement ventilation

$$Q_F = \sum_{i=1}^{n_A} \beta_0 F_0^{2/3} (h - z_i)^{5/3}$$

$$\approx \int_0^L \frac{n_A \beta_0 F_0^{2/3}}{L} (h - sx)^{5/3}\, dx$$

$$= \frac{3n_A}{8sL} \beta_0 F_0^{2/3} \left[h^{8/3} - (h - sL)^{8/3} \right]$$

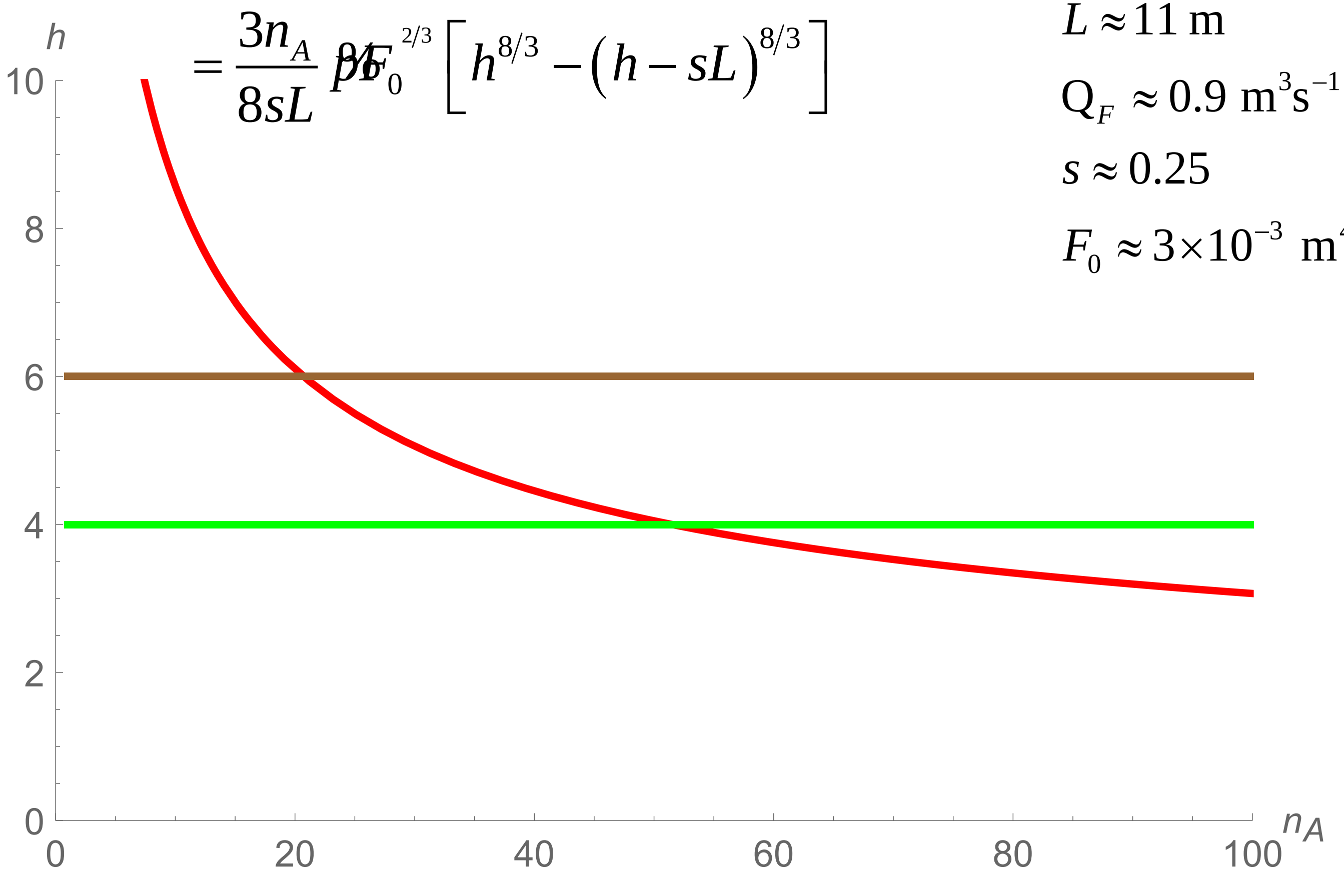
$$\beta_0 = \frac{6\alpha}{5}\left(\frac{9\alpha}{10}\right)^{1/3} \pi^{2/3} \approx 0.16$$

$L \approx 11$ m

$Q_F \approx 0.9\ \mathrm{m^3 s^{-1}}$

$s \approx 0.25$

$F_0 \approx 3\times10^{-3}\ \mathrm{m^4 s^{-3}}$



Many assumptions

- Masks
- Virtual origin on floor
- Unaffected by furniture and neighbours
- Fresh air distribution
- First-front horizontal

This room – displacement ventilation

$$Q_F = \sum_{i=1}^{n_A} \beta F_0^{2/3} (h - z_i)^{5/3} \qquad \beta = \frac{6\alpha}{5}\left(\frac{9\alpha}{10}\right)^{1/3} \pi^{2/3} \approx 0.16$$

$$\approx \int_0^L \frac{n_A \beta F_0^{2/3}}{L} (h - sx)^{5/3}\, dx$$

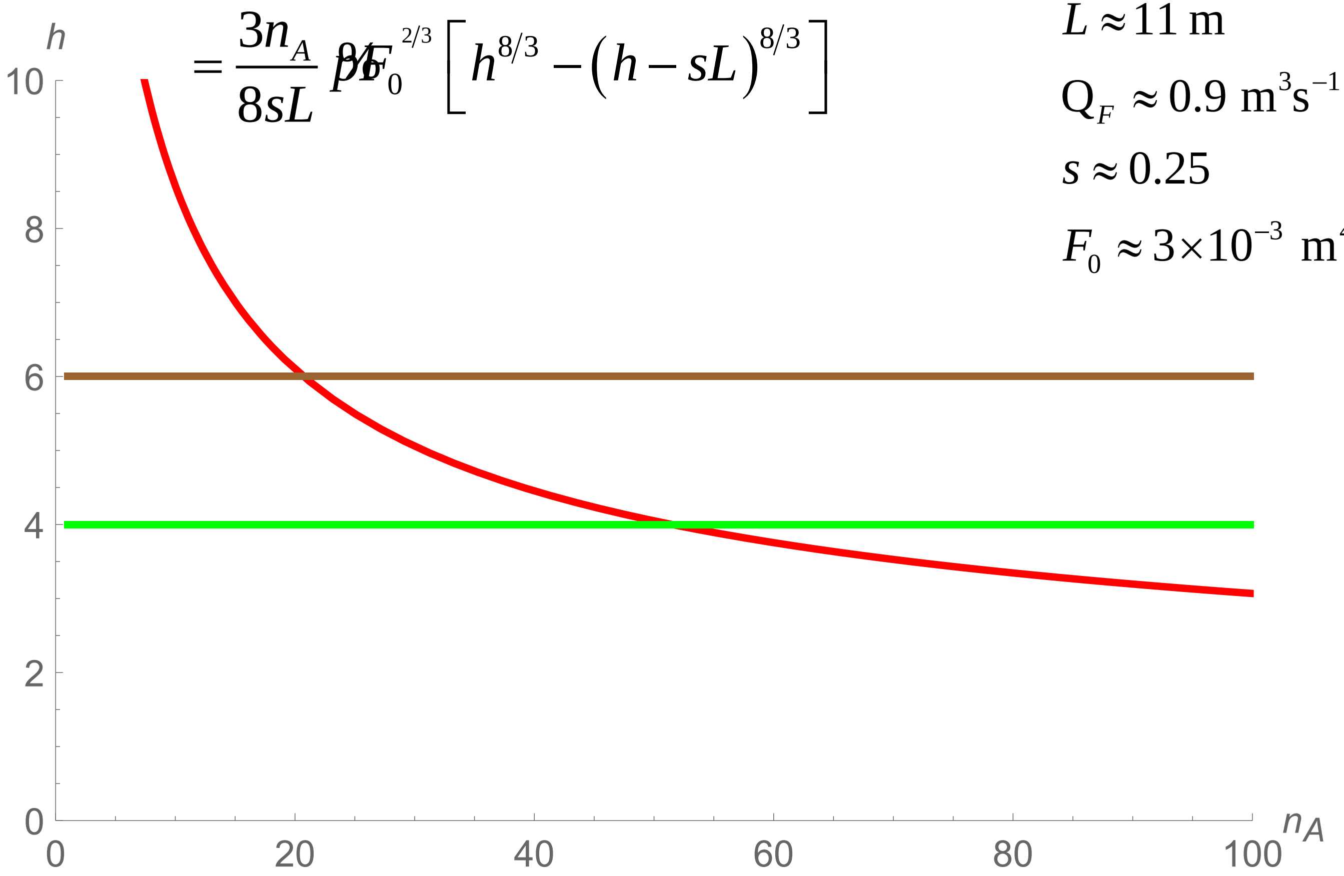
$$= \frac{3n_A}{8sL} \beta F_0^{2/3} \left[h^{8/3} - (h - sL)^{8/3} \right]$$

$L \approx 11$ m

$Q_F \approx 0.9\ \mathrm{m^3 s^{-1}}$

$s \approx 0.25$

$F_0 \approx 3\times 10^{-3}\ \mathrm{m^4 s^{-3}}$

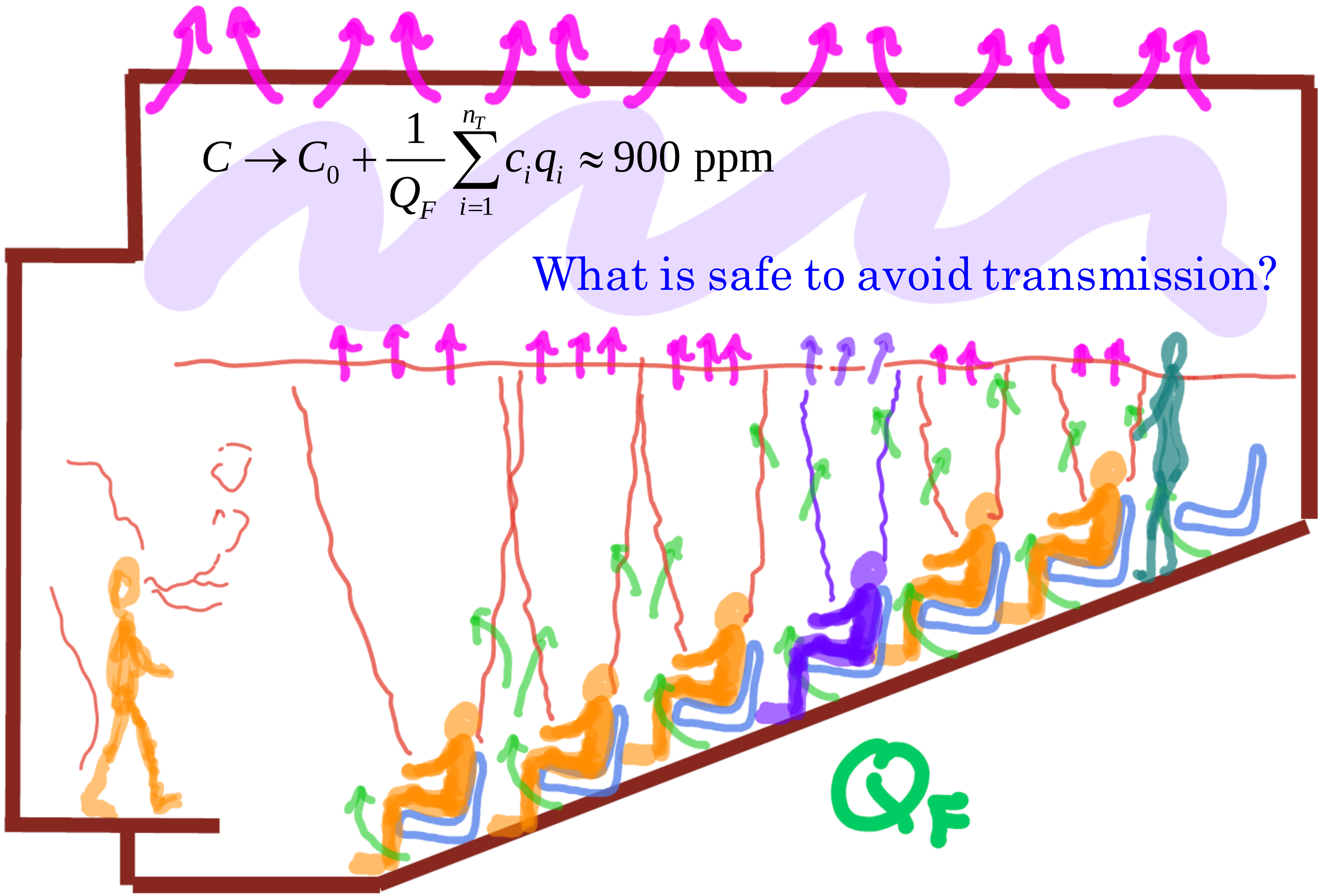


Many assumptions

- Masks
- Virtual origin on floor
- Unaffected by furniture and neighbours
- Fresh air distribution
- First-front horizontal

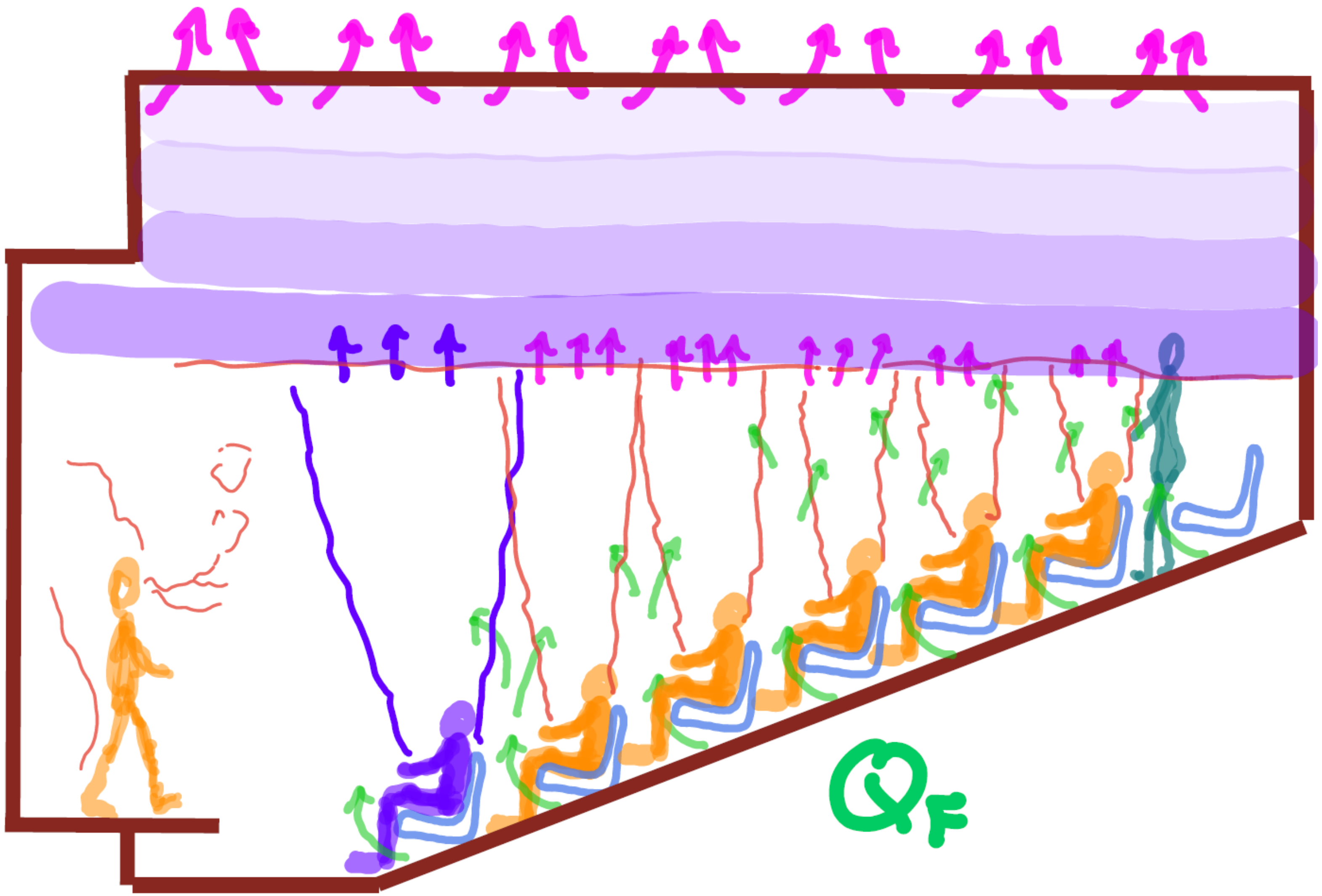
This room – displacement ventilation

UNIVERSITY OF CAMBRIDGE

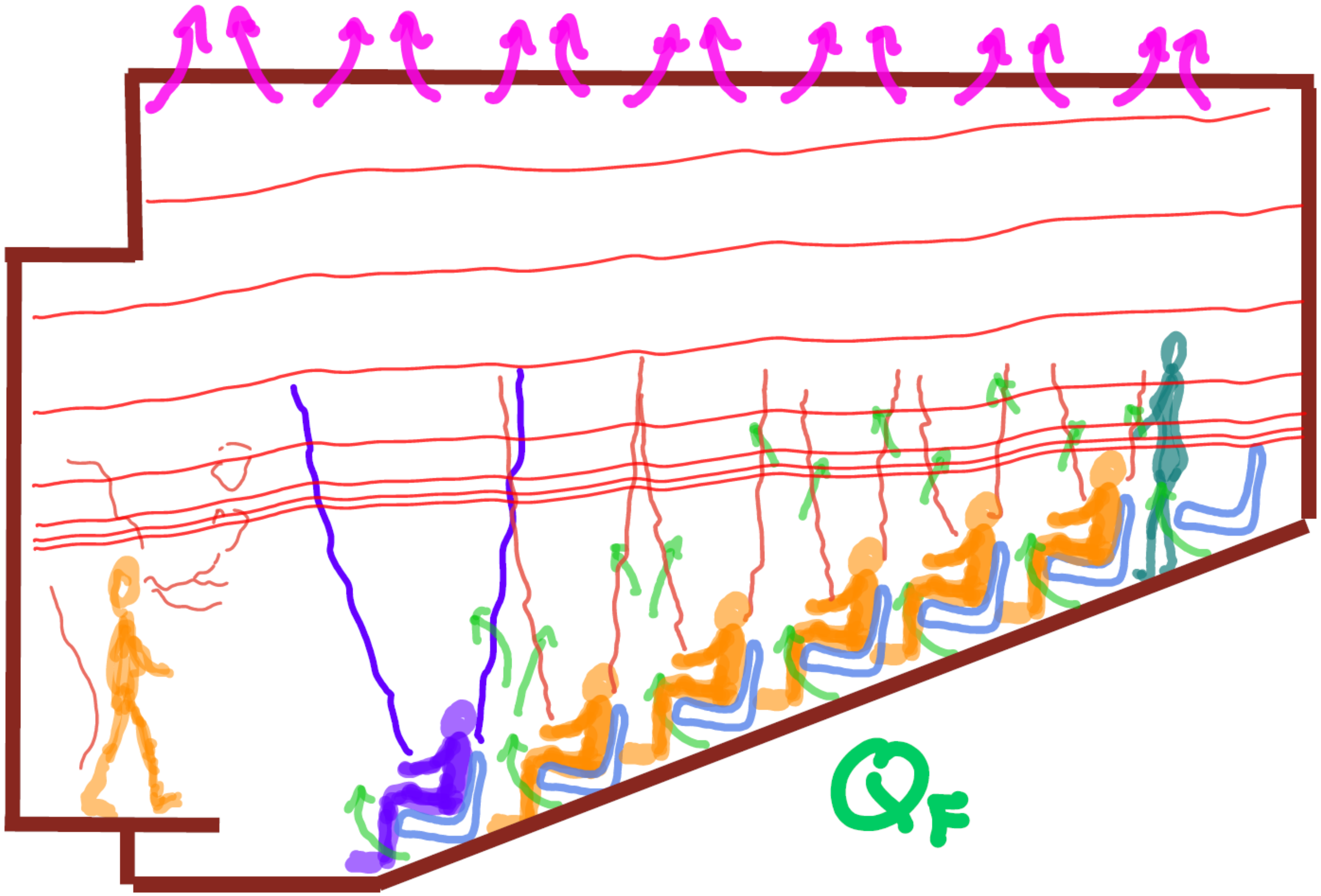


This room – displacement ventilation

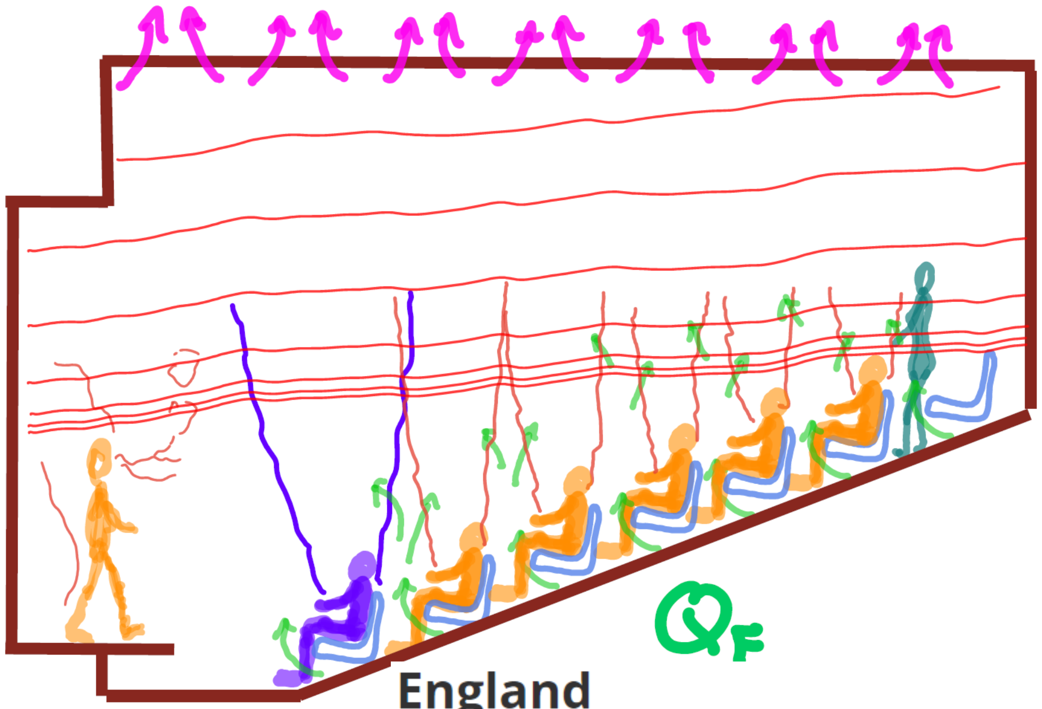
UNIVERSITY OF CAMBRIDGE



This room – displacement ventilation

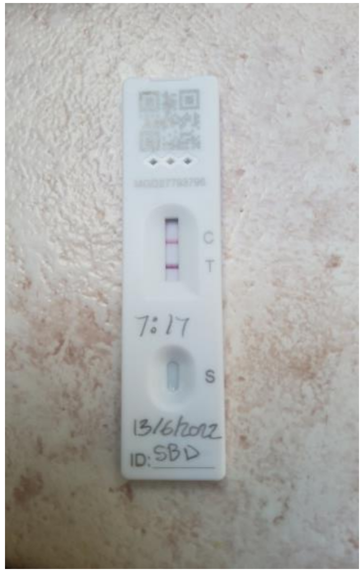


This room – displacement ventilation

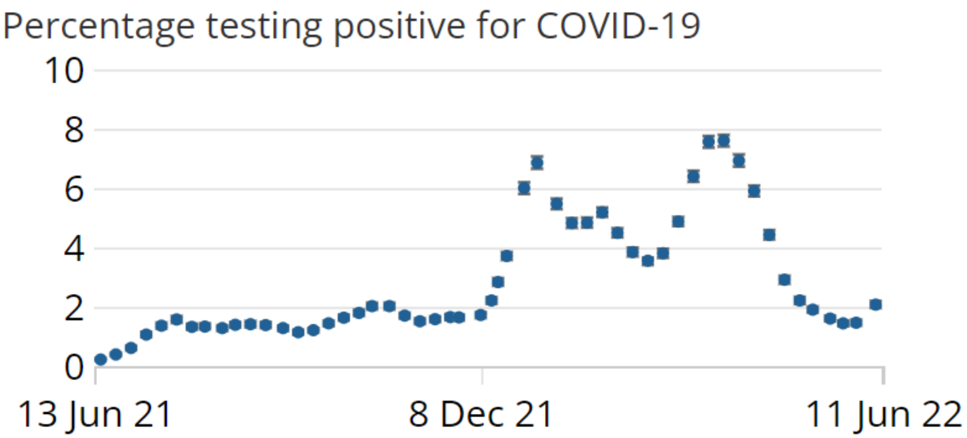


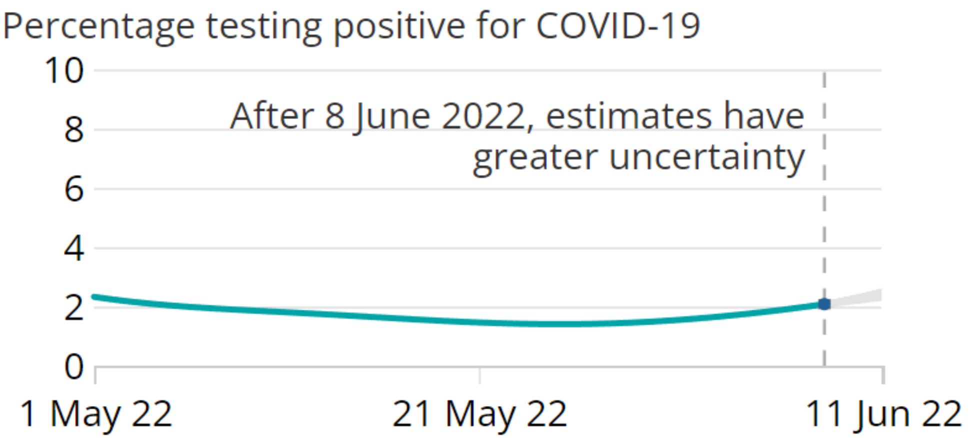
$$P(at\,least\,one) = 1 - P(none) \approx 1 - e^{-\lambda} \approx 92\%$$

Are those in the room typical of the population?



England





Modelling needs

UNIVERSITY OF CAMBRIDGE

Simple models

- Capture essence of how it *should* work, but lack details

Computational Fluid Dynamics

- DNS not feasible
- Generally ignore activity within room
- Difficulty modelling *entire* building
- Capture reasonable details of the consequence of assumptions
  - Assumptions invariably wrong
  - Conclusions *can be very sensitive* to assumptions (e.g. boundary conditions)

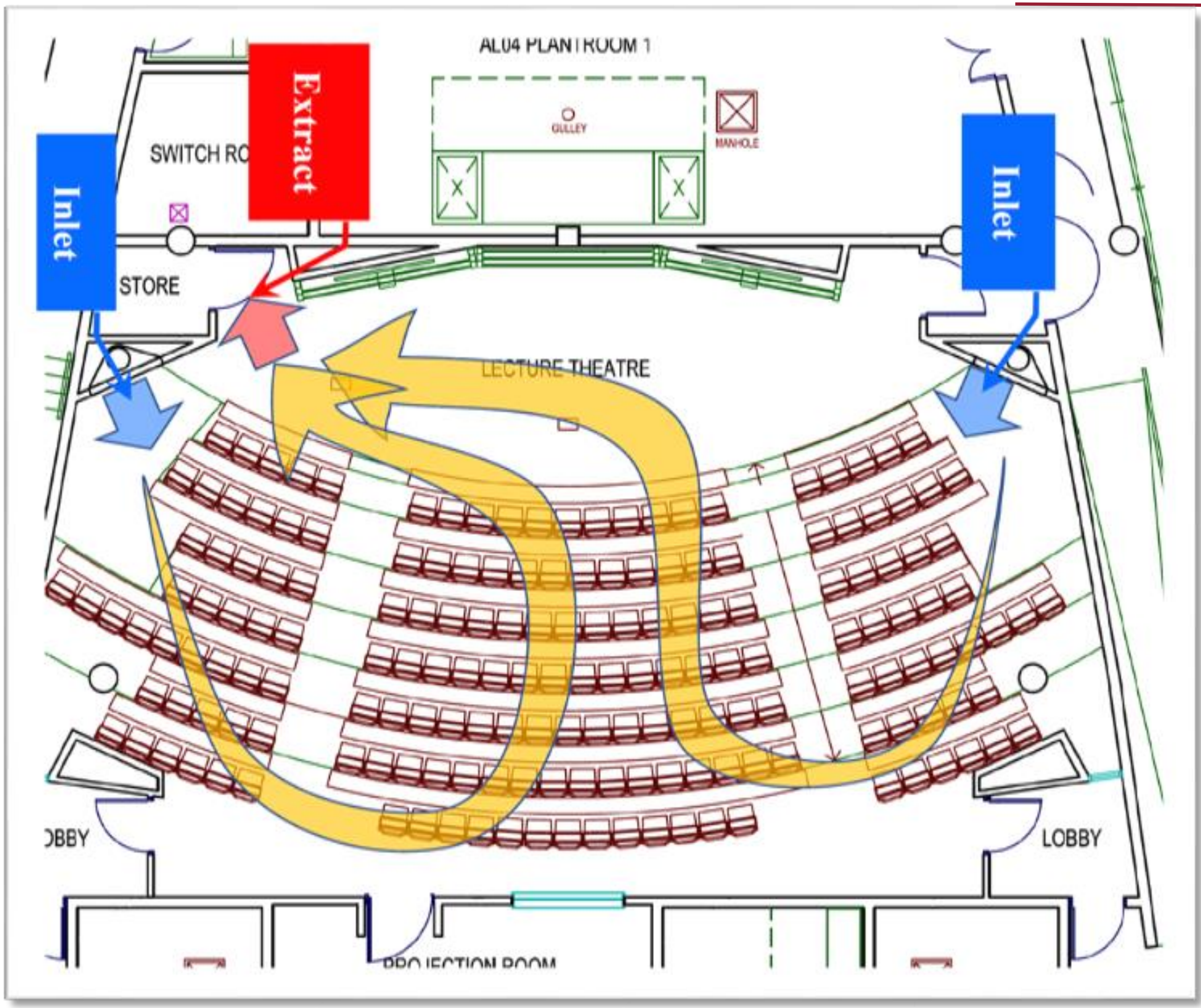
Value of current models

- Very enlightening
- Need easy way of identifying when they do not work

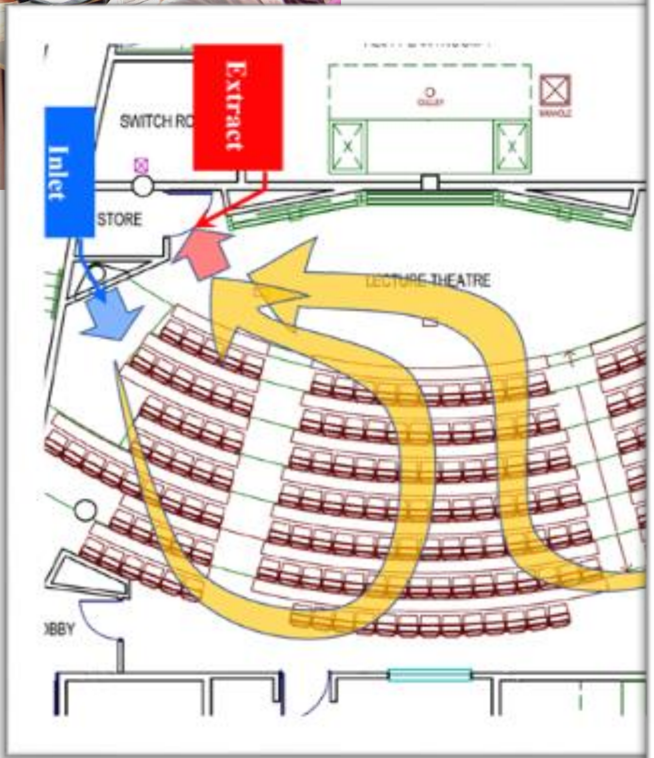
Many spaces have design ‘compromises’

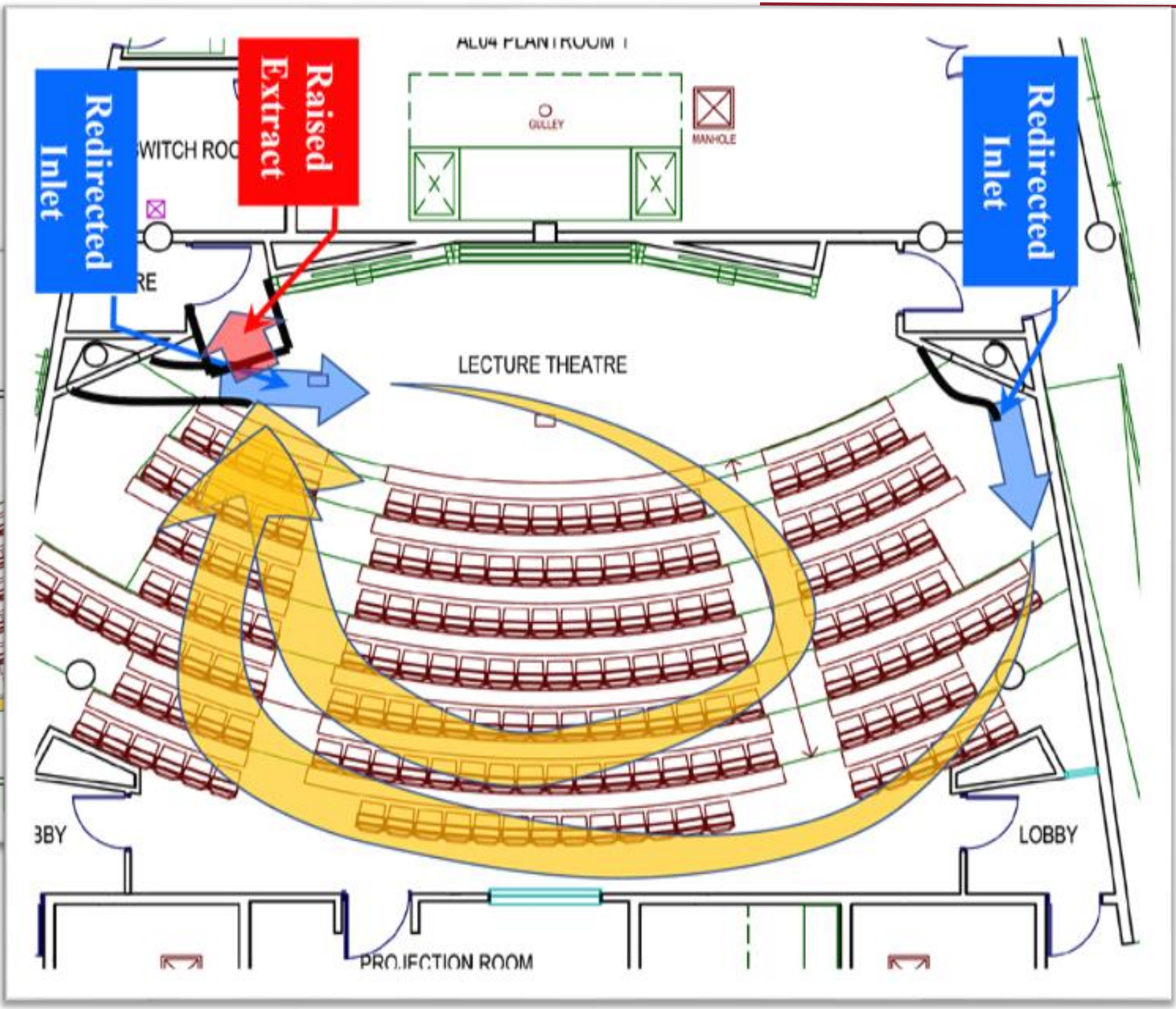
UNIVERSITY OF CAMBRIDGE

Many spaces have design 'compromises'



Many spaces have design ‘compromises’





Mixing ventilation

UNIVERSITY OF CAMBRIDGE

More common

- Cheaper
- Do not need raised floor

Design criteria

- Capital cost
- Space requirements/utilisation
- Thermal comfort
- Energy cost
  - Recirculation

…

- Air quality
- Infection transmission

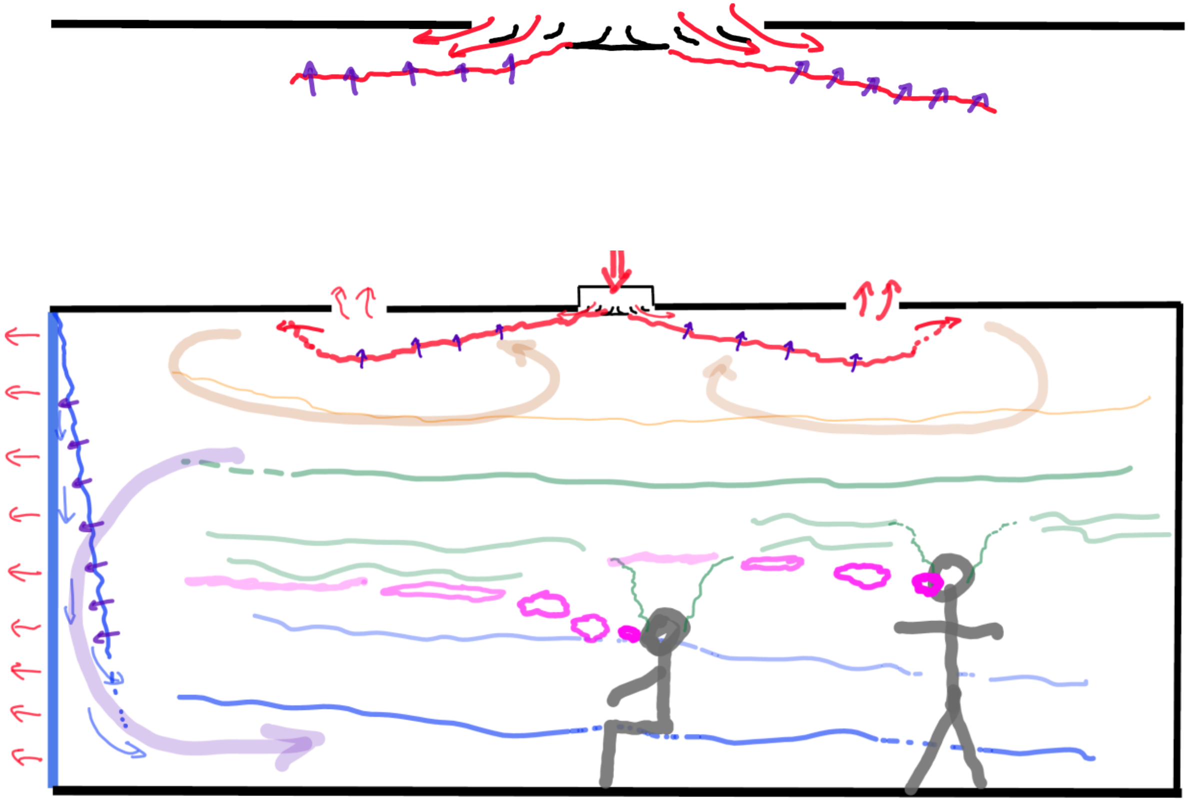
Recognise

- Higher Q_F required
  - Reduce recirculation
- Filtering recirculation *might* be possible
- Often designed for *cooling*
  - Conflict with heating requirements
  - May need to supply heating
- Sources/sinks of heat not accounted for
- Internal usage/equipment not accounted for

Mixing ventilation – are spaces well mixed?

UNIVERSITY OF CAMBRIDGE

Density stratification



Ventilation that is effective for cooling may be very poorly configured for heating, creating strong internal stratification

Ceiling jets good at distributing cooling, but lead to short-circuit when heating

In-room mixing and deflecting jet downwards helps

Natural ventilation

Increasingly common

- Often cheaper
- ‘Free’

Design criteria

- Capital cost
- Thermal comfort
- Energy cost
  - Heating only

…

- Air quality
  - Sensitive to external quality
- Infection transmission
  - The Victorians worried about it, but…

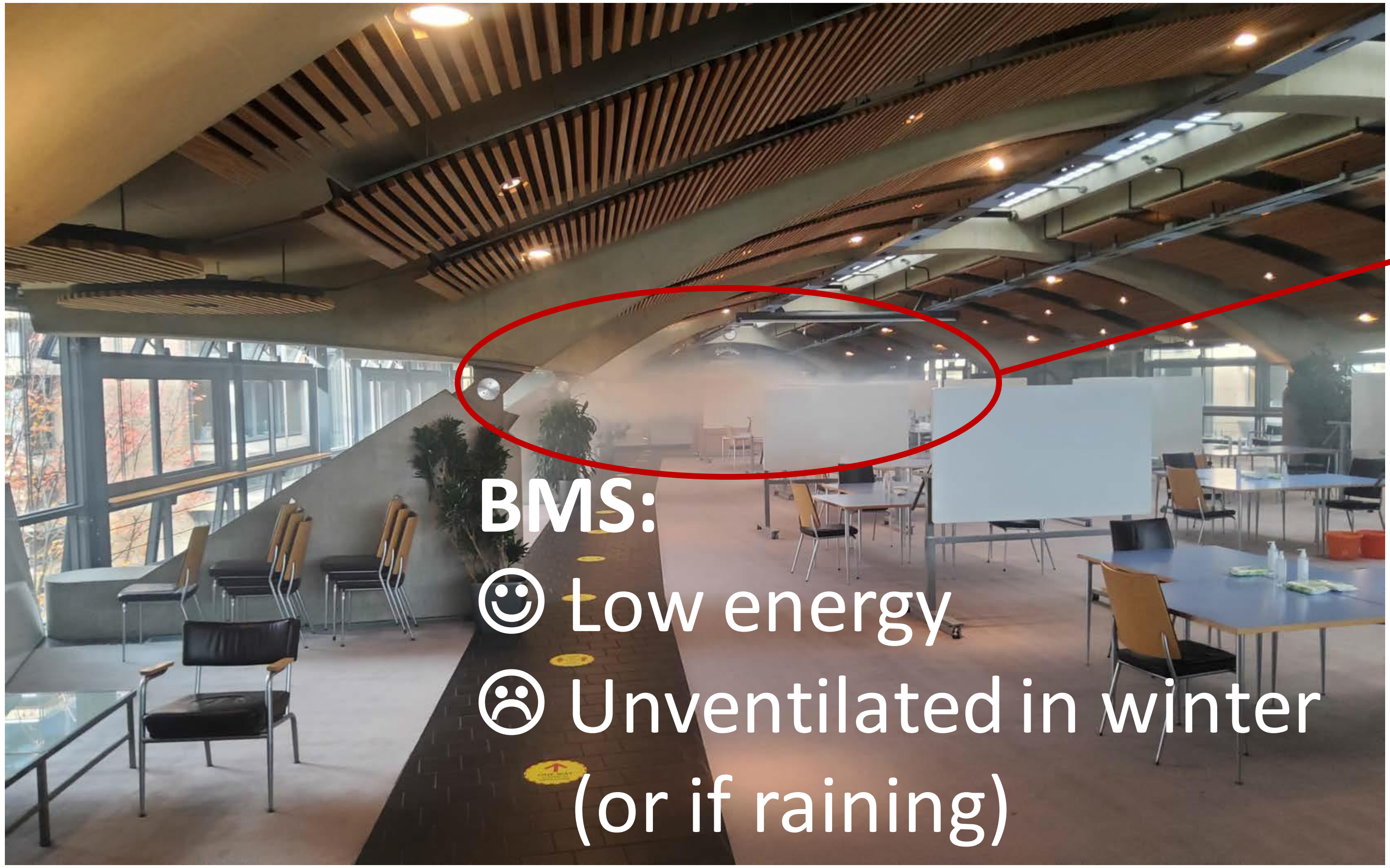
Recognise

- External conditions dominate
- ‘Opening more windows’ not always possible
- Often designed for *cooling*
  - Conflict with heating requirements
- Occupant choice can be very harmful
- Predicated on very simple models

The Victorians needed to be (and often were) better

Naturally (un)ventilated space

External vulnerability



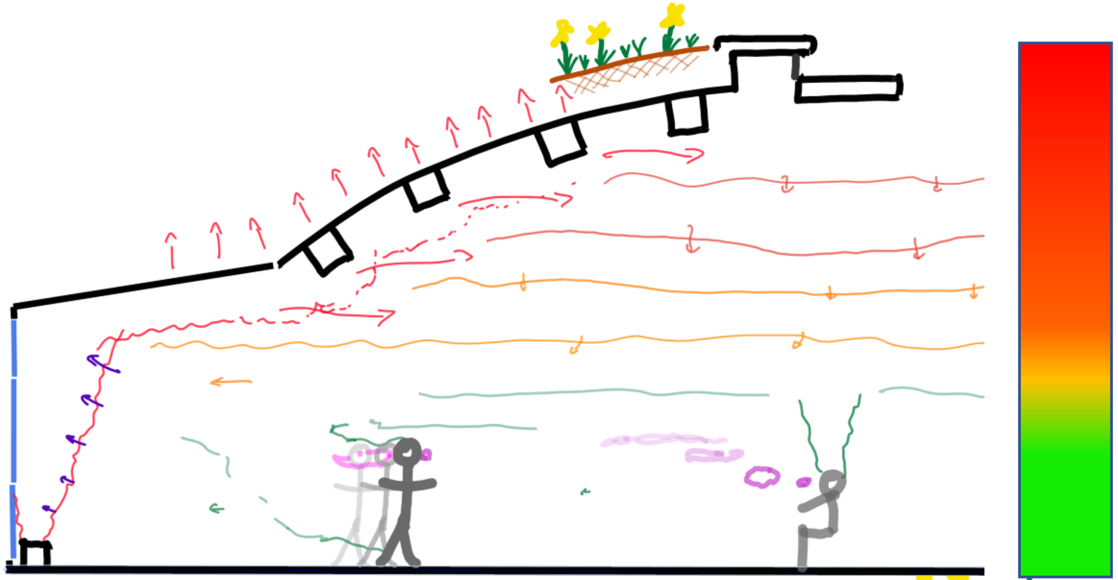
Natural ventilation often designed for effective at cooling and energy efficiency rather than winter air quality

Horizontal *and* vertical inhomogeneities

Naturally ~~ventilated~~ chilly space

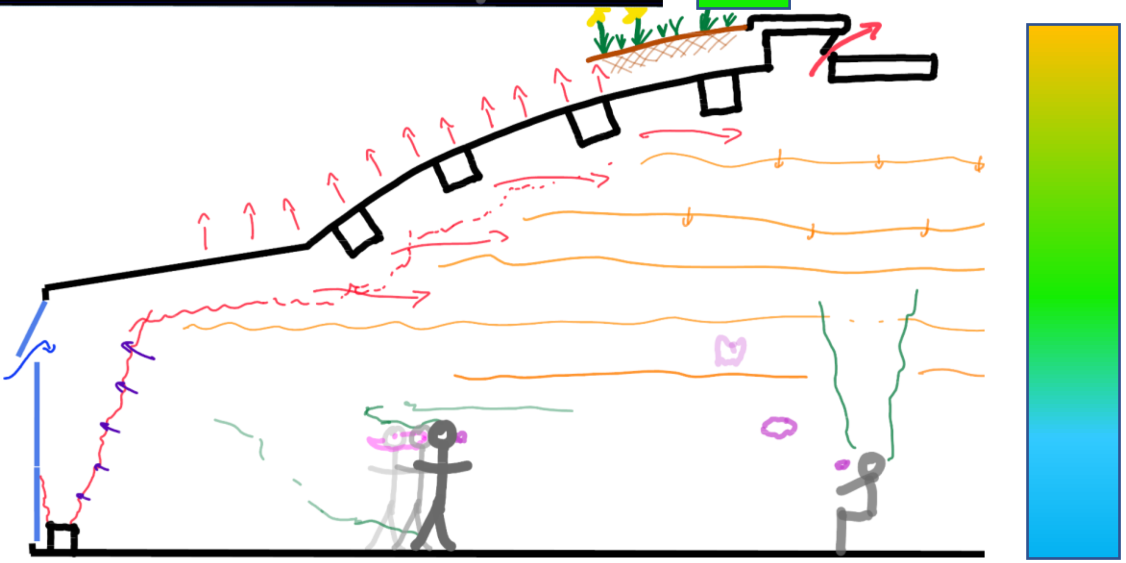
Operational priorities

Winter/BMS default: heating drives flow and generates stratification, but does not ventilate the interior



Thermally comfortable, but nearly no ventilation

Opening the *wrong* windows can make things worse



Thermally uncomfortable and high energy wastage, but *adequate* ventilation

Natural ventilation – uncertainties

UNIVERSITY OF CAMBRIDGE

External conditions

- Hugely important
- Pressure fluctuations over timescales of 10 s

Occupant decisions/actions

- Variable occupation
- Doors open/closed; frequency
- Windows/vents open/closed
- Building Management Systems (BMS)
- User overrides/controls

Dependencies

- Upwind/downwind differences
- Variable occupation

The space between

University of Cambridge

Access

- Generally doors between spaces
  - Transient or sustained openings?
  - Traffic?
  - Congestion, touch points…
- Almost all doors leak
  - Most spaces are not CL3 labs
  - Pressure differences

Circulation spaces

- Often ignored as *an individual* is only there transiently
- Ventilation may only be via *asynchronously* connected spaces
- Low air change rate

Hidden connections

- May be ‘*unknown unknowns*’

Interzonal flows

Hidden risks

Ventilation of circulation spaces often low priority

Conduit for transmission between spaces

Not everything is a simple room

Public transport

Private transport

Termini

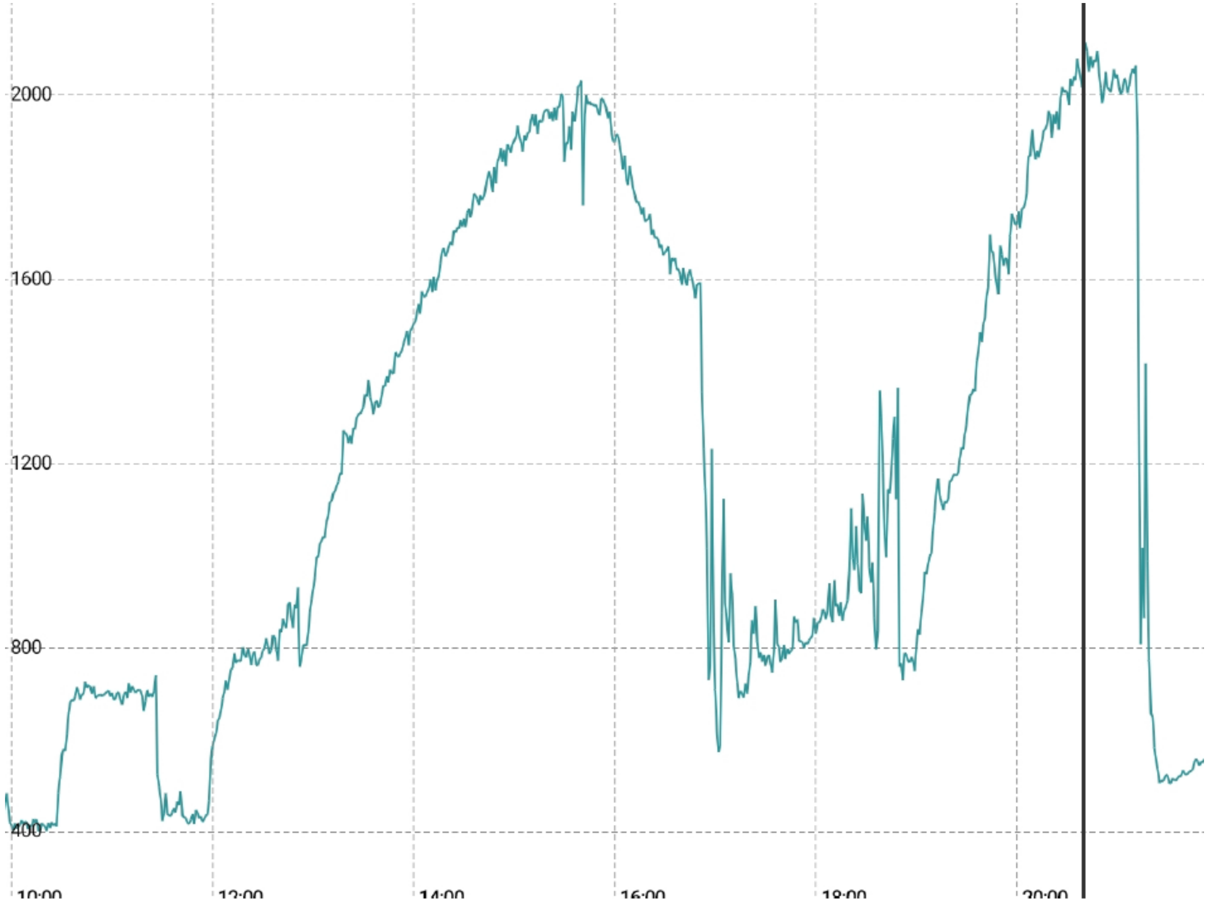
Streets

Underpasses

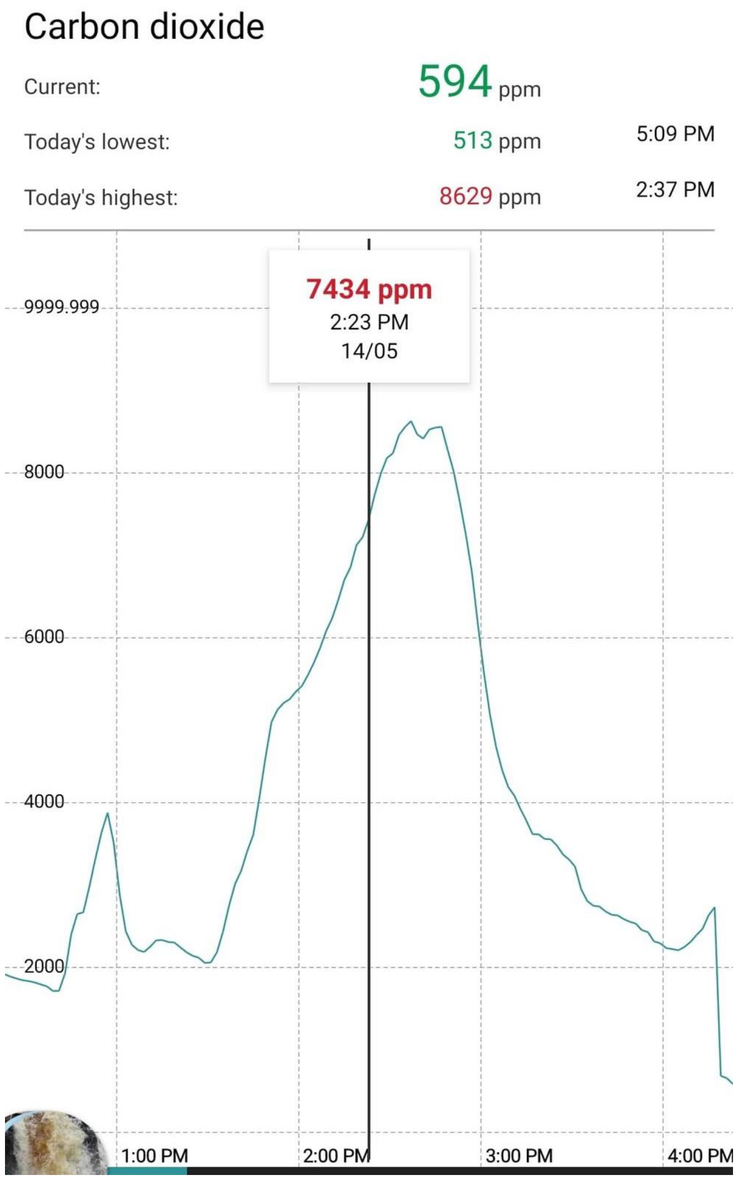
Stairwells

…

Other settings

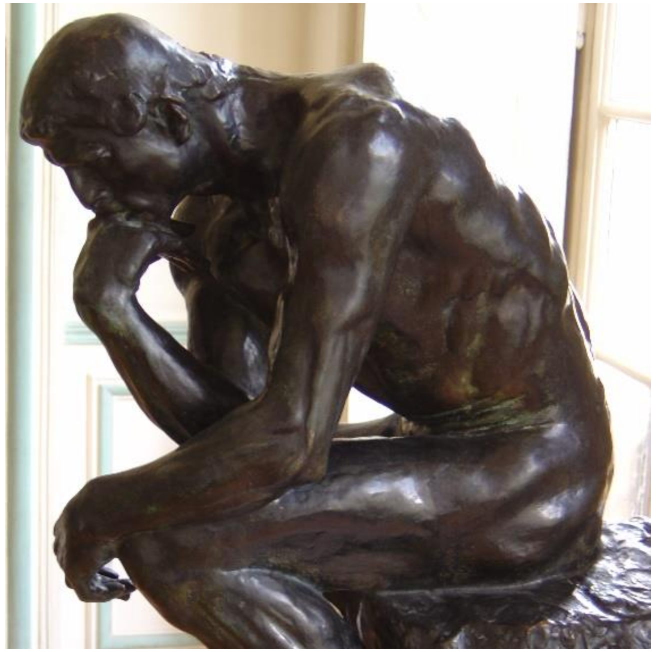


May 2022



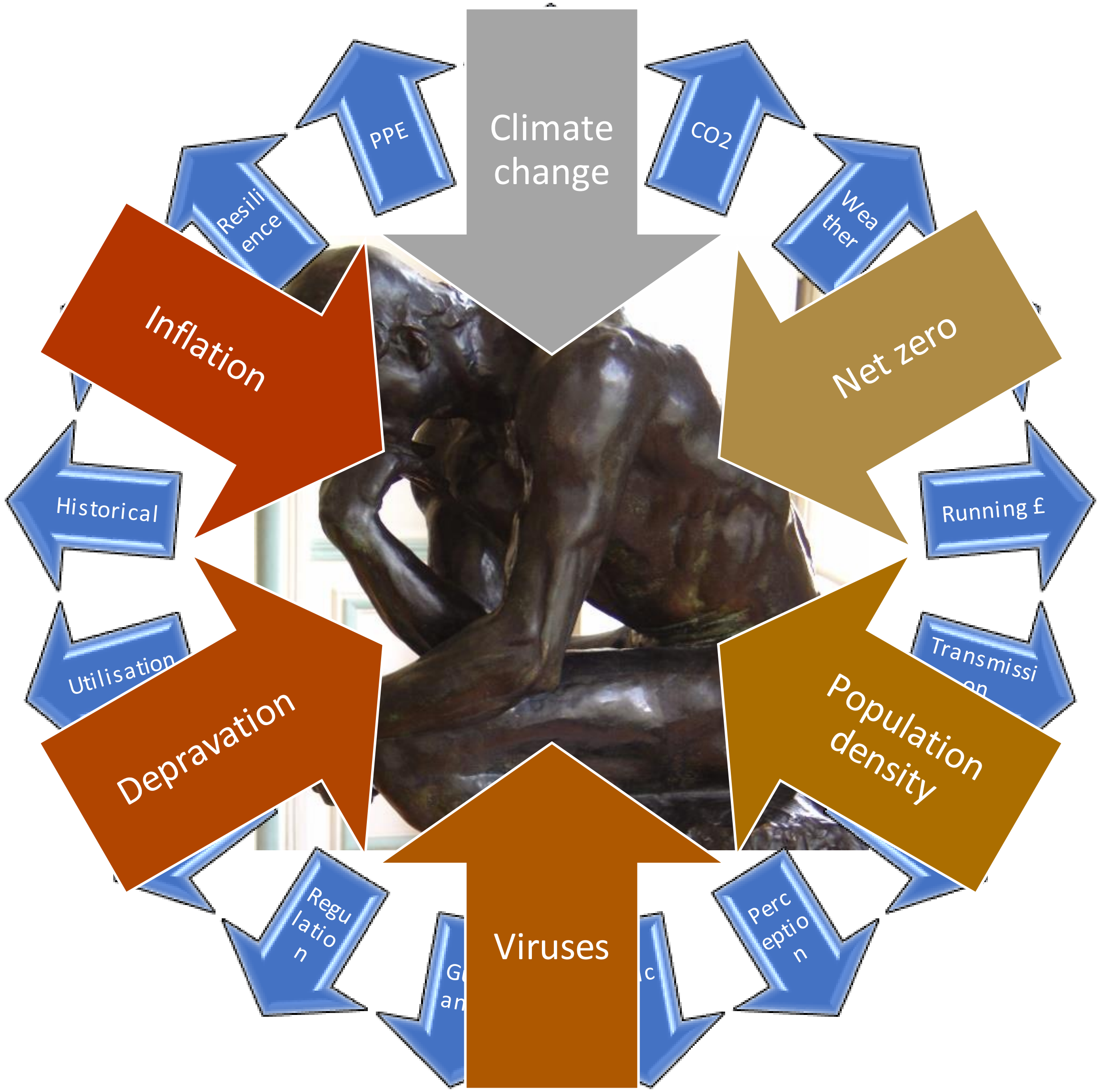
Risk of being overwhelmed

?



Risk of being overwhelmed

*Risk of being overwhelmed… **HELP!***



What do we need to do?

UNIVERSITY OF CAMBRIDGE

Reduce transmission

- Reduce exhaled aerosols

Improve air quality

- Reduce CO_2, VOC, particulates…

Reduce energy cost

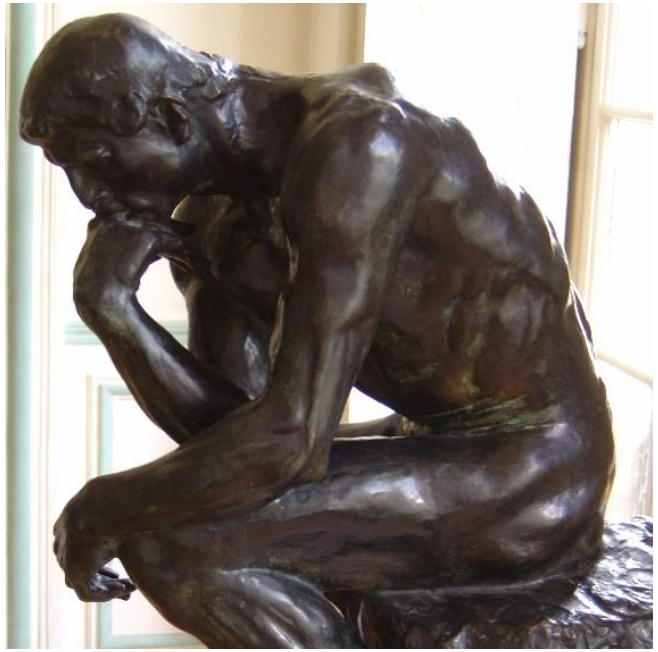
- Insulation
- Heat recovery

Minimise environmental impact

- Natural ventilation
- Embedded energy/carbon/wastage

Maintain/improve comfort

- Reset expectations
- Internal circulations



Where do we need to do it?

UNIVERSITY OF CAMBRIDGE

Monitoring

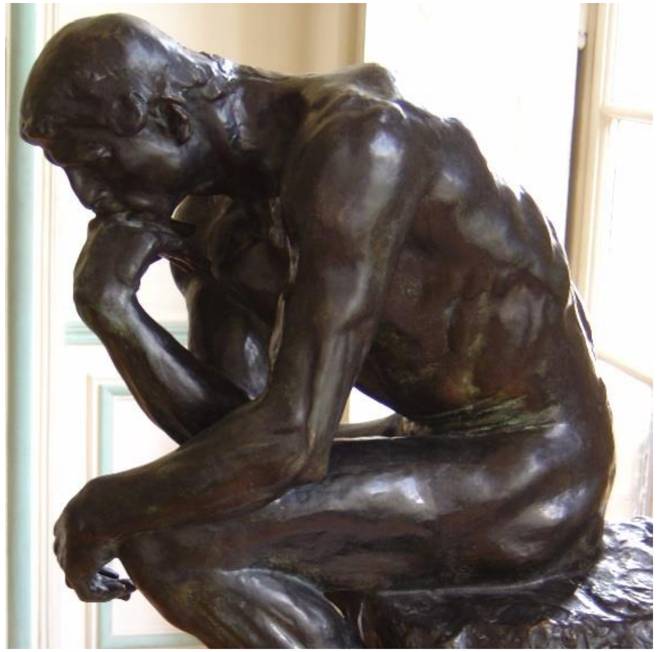
- What?
  - CO2? Occupation density? Duration? Proximity? Interactions? Activities?
- Where?
  - Indoors? Outdoors?
  - High-density spaces? Long-occupancy spaces?
  - Large-spaces? Small spaces?
- How?
  - Stand-alone monitors? Building-wide monitor arrays?
- Who?
  - Building managers?

Changes

- Operating strategies
- Infrastructure
- Behaviour

…

?



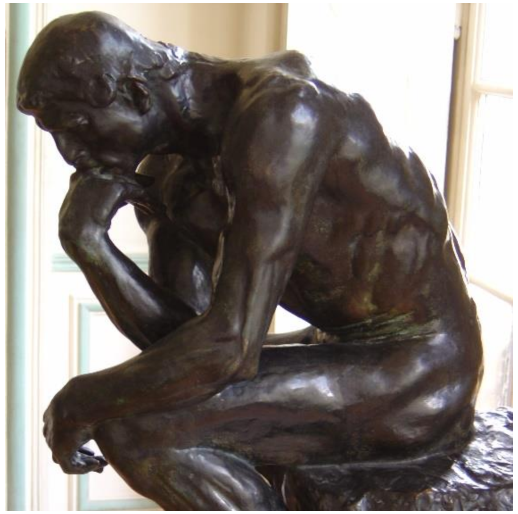
A tool?

UNIVERSITY OF CAMBRIDGE

More than just transmission

- The ‘environment for everything’
- Unifying different facets of our imagination and experience can produce real results to reduce the harm caused by human activities

$$e^{i\pi}$$



The *Friday Evening Club*

Stuart Dalziel (Cambridge)
Mark Kennedy (Imperial)
Prashant Kumar (Surrey)
Chris Pain (Imperial)

The *e*nvironment from the *i*ndividual *p*erspective

The environment from the individual perspective

UNIVERSITY OF CAMBRIDGE

enviroJewels

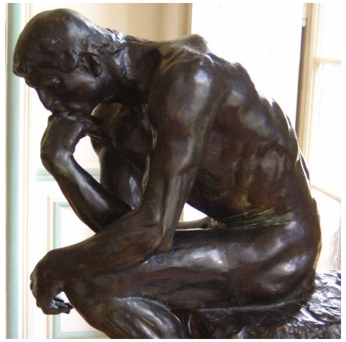
- Sensors worn as smart jewellery
- Low-power Bluetooth
- Low-cost

Sensors

- Proximity
- CO_2
- Temperature
- Humidity
- Pressure
- Sound level
- Light level
- Motion
- Compass
- TVOC

…

$$e^{i\pi}$$



Smart phone

- Current environment
- Cumulative environment
- *Post hoc* risk analysis

Cloud

- Integration with fixed sensors
- Integration with *nearby* sensors

Opportunities

- Machine learning
- Agglomeration
- Hot-spot identification
- Route planning
- Risk *prediction*
- Prioritisation strategy

…