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Editorial

Four principles for achieving good indoor air quality

> Everything should be made as simple as possible, but not simpler.
>
> Albert Einstein

Great scientific achievements are often expressed in simple terms. Consider Newton's second law: force equals mass times acceleration. Or the first law of thermodynamics: energy is conserved. Or Einstein's equation describing the interdependence of energy and matter: $E = mc^2$. These truths bring light to darkness and allow us to see order in what otherwise appears chaotic. Among my favorite examples is the ideal gas law: $PV = n\mathrm{R}T$. Consider an ordinary room, with a volume of 50 m^3, an air temperature of 293 K, and a pressure of 1 atmosphere. From the ideal gas law, we *know* that the room contains 2080 moles of air. Furthermore, because the molecular weight of air is 29 g/mol, we also know that the room contains 60 kg of air. From Avogadro's number, we understand that the room's air comprises 1.25×10^{27} molecules, a stunningly large number. From the kinetic theory of gases, we know that the molecules are traveling at a mean speed of 460 m/s and that they travel an average distance of 0.065 μm before colliding with another molecule. From these last two points, we infer that the average travel time between collisions is a mere 0.14 ns. Overall, each of the 10^{27} molecules in the room experiences an average of 70 billion collisions per second with other molecules. And yet, $PV = n\mathrm{R}T$. Order out of chaos!

I have been wondering whether our community—those concerned with indoor environmental quality and health—knows enough now to articulate simple rules for achieving good indoor air quality. Such rules should not be expected to be as universally true as are laws in the physical sciences. Key tests of their value might be these. Are they easily understood? Are they mostly true? (And when not beneficial, are they also not harmful?) Do they help guide research and practice?

It seems that we do indeed know enough to articulate a concise set of principles for achieving good indoor air quality. Here is a trial set: four ideas expressed in twelve words, listed in priority order.

- Minimize indoor emissions.
- Keep it dry.
- Ventilate well.
- Protect against outdoor pollution.

The following paragraphs elaborate on the broader intent behind these concise statements. A brief critique is provided, stating some recognized limitations. Also, a few thoughts are expressed about ongoing research needs so that these rules can be more widely understood and more effectively practiced. A caveat: these guidelines focus on indoor *air* quality, a subset of indoor environmental quality. Other important issues are not addressed in these principles, such as maintaining thermal comfort and limiting noise pollution.

Minimize indoor emissions

A broadly applicable environmental principle is to control pollution at the source whenever possible. Ample evidence argues that source control is essential in indoor environments. For many pollutants, when indoor emissions are high, so too will be pollutant concentrations, regardless of other factors. An extreme and tragic example of failing to follow this rule is reflected in fatal accidental poisonings from carbon monoxide inhalation. Regardless of other factors, when indoor emissions are excessive, adverse consequences are large.

For some sources, effective control is achieved with local exhaust, with or without containment. Including this idea, perhaps the principle would be better stated as 'minimize *uncontrolled* indoor emissions'. The containment and exhaust approach is practiced in managing emissions produced by combustion for heating (the chimney or the flue), by cooking (the range hood), and from toilets (local exhaust from an enclosed room). A second source control approach is more administrative or regulatory. Certain polluting activities, such as tobacco smoking, are prohibited in many public indoor spaces. A third key method—practiced to some net benefit in reducing exposure to volatile organic compounds—is to limit emissions from building materials, from furnishings, and from products used indoors. Implementing this strategy might entail manufacturers changing product formulation or altering processes to reduce emissions from finished products. Alternatively, the approach might be pursued via a change in operations within a building, such as when chemical-based cleaning is done, what cleaning products are used, and in what quantities.

In practice, the goal of minimizing indoor emissions can be elusive. Formally, the *minimum* emission rate is zero. That goal seems unattainable for any particular building across all potentially harmful chemicals. Some emissions of some contaminants are inevitable. Good practice would achieve emissions sufficiently low so that any residual health risk is negligible. The large number of manufactured chemicals, the diverse products in which they are used, variable indoor environmental conditions, and the lack of sufficient knowledge about health consequences of exposure contribute to large and as yet unsolved challenges in translating a good principle into good practice. Furthermore, even in cases in which there is sufficient knowledge as a basis for action, we may lack the means or motivation to effect change at the necessary scale. Such is the case for two classes of combustion processes that continue to impose major health risk burdens for those exposed: using unprocessed solid fuels in primitive stoves for cooking and smoking tobacco in indoor environments. Important topics for ongoing research to support emissions reduction from indoor sources include (i) developing an improved understanding of the specific chemical and particulate emissions that occur from products and processes indoors, (ii) characterizing the factors that influence these emissions, (iii) developing insight into how indoor emissions influence exposures, and (iv) understanding how exposures contribute to health risks.

Keep it dry

Remarkably strong and coherent epidemiological evidence shows that dampness in buildings is associated with an increased risk of adverse respiratory outcomes. A recent review by Mendell et al. (2011) concluded that there is 'sufficient evidence of an association between indoor dampness-related factors and a wide range of respiratory or allergic health effects, including asthma development, asthma exacerbation, current asthma, ever asthma, dyspnea, wheeze, cough, respiratory infections, bronchitis, allergic rhinitis, eczema, and upper respiratory tract symptoms'. The risk factors that have shown the strongest associations are qualitative: subjective evaluations of visible dampness, water damage, visible mold, and mold odor. The causal agents responsible for these associations are not known, which poses a scientific challenge meriting further research. Inhalation exposure of fungal spores, or fragments of fungi, or their chemical byproducts are candidates. Bacterial agents associated with damp conditions may contribute. So, too, may chemicals released from building materials at rates that may be significantly influenced by moisture, such as formaldehyde and 2-ethyl-1-hexanol. Detritus from dust-mites, cockroaches, and other pests whose abundance depends on indoor moisture conditions might be a factor.

Even without understanding the causal links, the practical goal of protecting health may be effectively pursued by focusing on the control of 'evident dampness.' Contributions to the effective management of excessive indoor moisture may be achieved by pursuing the first and third principles. Indoor emissions of water vapor can be limited, for example, by the use of local exhaust for cooking and bathing. Ventilation contributes to the management of indoor dampness, too, as can enhanced air movement to hasten the rate of evaporation from surfaces that have become temporarily wet.

However, managing moisture indoors has aspects that require attention beyond emissions control and ventilation. Building envelopes must have integrity to prevent the intrusion of water from outdoors. Episodes that accidentally soak indoor materials such as a flood, a plumbing leak, or a breach in the integrity of the building envelope must be managed rapidly and effectively so that the wet materials are rapidly dried and any materials that become moldy are expeditiously replaced. Buildings must be designed, built, and operated in a manner that is climate appropriate so that visible and hidden interior surfaces are maintained at temperatures well above the dew point of their adjacent air. Air conditioning systems must be designed and operated to manage well the water that is condensed from humid outdoor air.

The prevalence of evident dampness is large. Spengler et al. (1994) reported that half of surveyed households in 24 US and Canadian cities had a dampness-related condition (water damage, water in basement, and/or mold or mildew). A recent assessment for 31 European countries concluded that 16.5% of households had one or more of damp, mold, or water damage (Haverinen-Shaughnessy, 2012). Large health and economic benefits could result from effectively controlling excessive indoor dampness. Mudarri and Fisk (2007) estimated that 4.6 million cases of asthma in the USA are attributable to dampness and mold exposure at home with an associated annual cost of $3.5 billion. In summary, the scale of current problems associated with excessive dampness is large and so are the potential benefits of improved practice.

Ventilate well

The importance of ventilation as a factor influencing indoor air quality is widely recognized. Good ventilation is needed to limit the accumulation of emissions that cannot be avoided, such as bioeffluents from building occupants. Local exhaust ventilation can effectively contribute to controlling localized indoor emissions. Ventilation is inadequate as a means of controlling pollutants whose uncontrolled indoor emission rates are excessive.

To ventilate well, it is necessary to ventilate sufficiently and effectively. The quantity of air provided per time must be adequate for the local needs and that air should be distributed appropriately. Ventilation standards express sufficiency in various terms, such as a minimum volume flow rate per occupant plus another increment per building floor area or as a minimum air change rate. To be effective, ventilation air with low contaminant levels should be supplied to occupants. Conversely, ventilation is effective to the degree that exhaust air removed from an indoor environment is more contaminated than the average air in the indoor space.

The cumulatively large energy requirements associated with building ventilation are an important constraint on ventilation practice, a constraint that is becoming more stringent with time owing to growing concerns about the environmental consequences of energy use, especially from fossil fuels. At many times in most locations on earth, energy is required to thermal condition ventilation air. Energy is also used to power the fans that move air in mechanically ventilated spaces against the resistance of ducts, thermal-conditioning coils, and filters.

A large challenge associated with building ventilation derives from commingling the means of providing thermal comfort with the means of ventilating for indoor air quality purposes. In mechanically ventilated buildings, air is commonly used as the working fluid to deliver or remove heat from occupied spaces. Because air has a low heat capacity, large volume flow rates are required for that purpose, much larger than necessary for effective ventilation. It seems probable, with the power of modern information technology and controls, that decoupling these functions will enhance opportunities to develop effective and efficient systems that achieve good thermal comfort and good indoor air quality. On the scientific front, we need a stronger understanding of how ventilation rates and distribution systems influence indoor pollutant concentrations and associated health risks.

Protect against outdoor pollution

Our community tends toward myopia in thinking about the causes of indoor air pollution. We are rightly concerned about emissions from indoor sources, about protecting against indoor dampness, and about the sufficiency of ventilation as well as its effective delivery. And we regularly fall short of the needed attention to ensure that ventilation air is of suitable quality for its intended purpose. One of the stark manifestations of this problem is the common reference to the outdoor supply air stream in ventilation systems as *fresh*.

Outdoor air is commonly polluted and often sufficiently so that it is unhealthful to breathe. Outdoor air in urban environments, where most people now live, is more commonly unhealthful than outdoor air in rural environments. However, even in rural communities, outdoor air may be polluted from myriad sources, including combustion for cooking, heating, agricultural, industrial, and waste-management purposes. Many countries have regulatory programs in place to monitor outdoor air pollution and to develop and implement control measures aimed at meeting health-based standards. In countries with advanced economies, those standards are not yet consistently met, even after decades of effort. In countries with developing economies, the outdoor air pollution levels are commonly much higher than in countries with advanced economies.

The two pollutant classes of greatest health significance in outdoor air are fine particulate matter ($PM_{2.5}$) and ozone. Mature technologies are available for removing both pollutant classes from air streams. Reviewing the health benefits of particle filtration for buildings, Fisk (2013) concludes that ‘the largest potential benefits of indoor particle filtration may be reductions in morbidity and mortality from reducing indoor exposures to particles from outdoor air’. Weschler (2006) has noted that a substantial proportion (25–60%) of daily ozone intake occurs indoors. He also noted that activated carbon or chemically impregnated filters could be used to control ozone in mechanically ventilated buildings and that the temporal pattern of ventilation might be managed for the purpose of reducing exposure to ozone in naturally ventilated buildings.

Indoor air quality is a complex subject. The global population is approaching 10^{10} people who inhabit on the order of 10^9 distinct buildings. The number of chemical species in indoor air of potential concern for human exposure is uncertain; a lower bound might be the high-production volume chemicals, which number 2200 in the USA alone. Indoor environmental conditions that influence exposures vary in space and time. Health risks may depend in complex and subtle ways on factors such as the time pattern of exposure, as well as on the age, gender, genetic heritage, and underlying state of health of the exposed persons. Developing a better understanding of the major aspects of this system through strong research should be a priority for societies that can afford the investment. At the same time as we acknowledge and investigate the complexity, we should also seek to understand and communicate the core truths of what we are learning about indoor environmental quality. In doing so, we would do well to adhere to Einstein’s dictum: make everything as simple as possible, but not simpler.

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