

Indoor Environmental Control Systems: Mechanical HVAC Systems

The building enclosure and site are generally not sufficient to provide the desired indoor environment for most buildings. Hence, supplementary means are employed to provide the additional heating, cooling, ventilation or lighting, needed. Plumbing is another system necessary for most building occupancies. This document will cover only the temperature and humidity control and ventilation aspects.

Although Heating Ventilating and Air Conditioning equipment (HVAC) is the common terminology, Indoor Environmental Control Systems (IECS) is likely more accurate and more inclusive of all of the functions. Today “air conditioning” is synonymous with “cooling” to most people. Originally, however, air conditioning included the removal of particles, the addition or removal of humidity, and the cooling of air. This confusion in terminology causes many practical problems in modern buildings, especially with regard to humidity and pressure control.

Functions

1. Fresh Air & Ventilation

In buildings with functional air barriers, a health requirement is the provision of fresh air, typically at about 5 to 10 liters per second per person. This provides oxygen (which is a small portion of the air) and dilutes and/or removes pollutants. This can be provided naturally (if carefully designed) or through mechanical means.

2. Heating

Some heating may be required to make up for air leakage and conduction losses if sufficient internal heat is not generated.

3. Cooling

In many climates cooling is required to remove heat generated internally and from conduction and air leakage.

4. Dehumidification/humidification

Adding humidity to the air is easy, but dehumidification is difficult. This is often the most important function of so-called air-conditioning systems that are supposed to cool as well.

5. Filtration & Cleaning

Air picks up pollutants (dust, pollen, gases, etc) of all kinds as it moves around a building and as it enters a building from the outside. Hence it is often desirable to clean the air.

6. Pressure Control

Moving air into and out of a space changes its pressure with respect to air in all sides of that space. To control these pressures, passive (barometric dampers and separators) or active (fans and motorized dampers) means should be used.

These are essentially independent functions, although they are often combined within a specific system. Since each of these functions can generally be accomplished by a number of means, the total number of system combinations is large.

Mechanical Components

Heat Production

Conversion of fuel (electricity, natural gas, biogas, oil, coal, wood, sod) to heat. Most units include a heat exchanger, e.g., a hot-air furnaces converts fuel to heat and then transfer via a heat exchanger to air. A boiler does the same but transfers the heat to water.

Heat Pumping

The transfer of heat energy from cool to hot (opposite the natural direction). This is used to generate cooling in summer (as in so-called “air conditioning” units) and can extract heat from outdoors in winter. A fridge is also a heat pump. A heat pump needs a source and/or sink for transfer heat from and/ or to. Most are based on compression-cycle phase change, but some use heat to drive an absorption cycle (hence, propane powered fridges are possible). Small thermo-electric coolers (Peltier devices) can be used but are very inefficient and too small for buildings. A chiller is a heat pump that extracts heat from a liquid (usually water) which is then distributed around a building for cooling.

Distribution

The method used to distribute heat and cool depends on the working fluid: water, glycol, refrigerant or air. Fresh air must be distributed by ducts or directed through the building volume itself. Ducts that use air as a working fluid need to be large since air does not store heat very effectively. Water is much denser and stores much more heat. Hence a 20 mm diameter pipe containing hot water can deliver more energy than a 0.2 x 0.3 m duct. The working fluid may be moved by pumps, fans, gravity or natural convection.

Terminal Units

A terminal unit is a heat exchanger or terminal that delivers or removes heat, and delivers fresh air or removes stale air to the space to be conditioned. E.g., diffusers, radiators, fan-coil units, radiant panels/floors, radiant baseboards, room-side of ductless splits, etc.

Heat Rejection / Collection

Heat pumps need to collect (when heating) or reject (when cooling) heat. This source or sink is the air, ground, or surface water (lakes and rivers). Hence, heat pumps (see above) are classed as air-source, ground source or water source. In some cases the source or sink can be another part of the building or an industrial process. In many cases a heat exchanger is used between the heat pump fluid and the source/sink.

Heat Exchange

Heat exchangers come in a wide variety of shapes and designs depending on the fluids being used. Liquids to air typically use a finned series of tubes containing the liquid. Air must be forced over the fins at a reasonable speed (often about 2 m/s) to get good efficiency (small HX for heat transfer). Sometimes the HX is from air-to-air (as it is in a heat recovery ventilator) or flames-to-air (as in a furnace) or water-to-air (as in a fan-coil unit) or refrigerant-to-air as in a direct expansion (DX) coil. A direct contact heat exchanger is used on the form of cooling towers – see below.

Filtering & Cleaning

Some components filter and clean the air. This is done both to protect air handling equipment and to improve indoor air quality. While porous filters are the common method, water washing, UV exposure, and turbulent flow precipitators are other available methods. Planted walls and recirculating filters may be just as effective as filtering air delivered by the fresh air system.

Pumps and Fans

Air pressure to drive airflow is generated by fans, and pumps are used to generate pressure in liquids. An incredible range of different technologies are available to perform these functions.

Application Considerations

There are several concerns when choosing systems and equipment for a building's IECS

1. Cost of purchase and construction
2. Cost of operation
3. Environmental impact of 1 and 2
4. Impact on building design (e.g. duct size, noise, appearance, etc.)

In general all IECS consume energy and move mass (air and/or water). Hence, an assessment of the energy sources and sinks are worthy of review, since this is fundamental to how we classify systems.

Energy sources and sinks

Primary **energy sources** are almost all heat based, for example

1. fossil fuels combustion
2. biomass or biogas combustion (combined with oxygen)
3. nuclear energy that fissions to release heat
4. solar heat that is directly captured and/or concentrated
5. solar energy captured in the form of falling water (hydro), wind (wind turbines) and waves.

Electricity is NOT a source of energy; it is a form of energy transmission. Electricity is generated in a number of ways (fossil fuels, hydro, and nuclear are by far the largest share but wind and solar generated electricity are growing) with a range of efficiencies.

Heat generated from primary energy sources is often used to generate electricity. The higher the temperature of the heat, the higher its “quality” and the easier it is to efficiently transform this heat to mechanical and thereby electrical power. Burning fuels to produce electricity is generally inefficient. Efficiency varies from around 30% in nuclear plants to about 60% in the most efficient compound cycle natural gas turbines. The Carnot cycle limits the efficiency of combustion generated electricity to about 75% (but higher efficiency is possible if the waste heat can be used). The capital cost of a large natural gas powered plant is in the order of \$1500/kW peak, while high efficiency combined cycle plants cost in the order of \$2500/kW

Electricity can be generated directly from the sun (photovoltaics), but such systems presently capture only about 10 to 20% of bright sun that falls on their surface. More important than efficiency for building applications is the high capital cost – operating costs are nearly zero. The capital cost has fallen significantly, but under bright sunny conditions, the capital cost for the equipment to generate this electricity is still in the order of \$4000 to \$7000 per peak kW. Over a twenty year lifespan, the cost to generate electricity in this manner is in the order of \$0.25 to \$0.30/kWh in many Canadian locations and can be less than \$0.20/kWh in sunny climates. If the system must also store the electricity in batteries, the cost may be nearly double this.

Wind can be used to produce electricity at relatively low cost. Large (over 3 MW) turbines located in areas with steady high speed (over 6-7 m/s) wind conditions can generate electricity for less than \$0.05/kWh. Such large turbines are now available and are best sited along coastlines and off-shore to capture the best wind. The cost of electricity production for smaller wind turbines and less windy sites rises quickly. The amount of electricity that can be produced increases with the square of the diameter and the cube of the average wind velocity.

Both wind and solar generated electricity suffer from intermittency. This means that their peak production may not coincide with peak demand, but is at the whim of natural forces. A major advantage of hydro, natural gas and nuclear plants is that their peak capacity is available whenever needed.

Hydrogen is NOT a source of energy, but it can be a form of energy transmission. Efficiency of hydrogen production from primary energy sources (currently natural gas and hydroelectric) is about 65-70% although experimental methods of producing hydrogen from electricity show efficiencies of as much as 90%. Compressing, transporting and storing hydrogen consumes a considerable amount of resources and energy. Hence, electricity produced by burning coal, at 35% efficiency, then used to generate hydrogen at 65% efficiency, compressed into containers at 90% and burned in a fuel-cell at 50% efficiency would result in a system efficiency of $0.35 \times .65 \times .90 \times .50 = 0.10$ or 10%. Burning natural gas directly in a spark-ignited engine (eg, a good car engine) would have an efficiency of almost 30%, and a compression cycle engine would have an efficiency of closer to 40%.

Energy sinks

Energy sinks are defined as locations to which energy can be rejected. Energy needs to be rejected during cooling and to exhaust heat from inefficient equipment. In buildings energy sinks include

1. the air, usually next to the building, but air mixes so well the heat is quickly diluted and spread around
2. bodies of water such as the ground water, rivers, lakes, and ponds. The heat mixes less well in liquids, so larger or fast flowing bodies of water are preferred. Groundwater may eventually heat up if it does not move away subsurface.
3. Soil, usually the soil next to a building. Since heat cannot move easily through the soil, this is a limited sink, which must be emptied by other means from time to time (e.g., heat might be added in summer by the building and removed in winter by the air).

Heat Collection and Rejection – terminal units

Heat energy may need to be collected/rejected in a space or to a sink. These are called *terminal units* when used within a room, since this is the end of the energy flow cycle from a mechanical engineers point of view.

- **Within conditioned space**

Terminal units may be as simple as a *diffuser*, that is, a grill that allows hot air to mix with cooler air in the room, thus heating the space. If the supplied air is cold, heat is removed.

Fan coil units are another means – room air is blown over a finned surface by fans. In this way heat is supplied or removed from a space. The coil may be heated by electric resistance heaters (the toaster approach) or hot water or refrigerant or cooled by cold water or refrigerant.

Convectors, heated or cooled panels and finned coils, are an essentially passive means of collecting or rejecting heat in a space. Hot or cold fluids are usually used, although electric resistance can also be used to provide heating only.

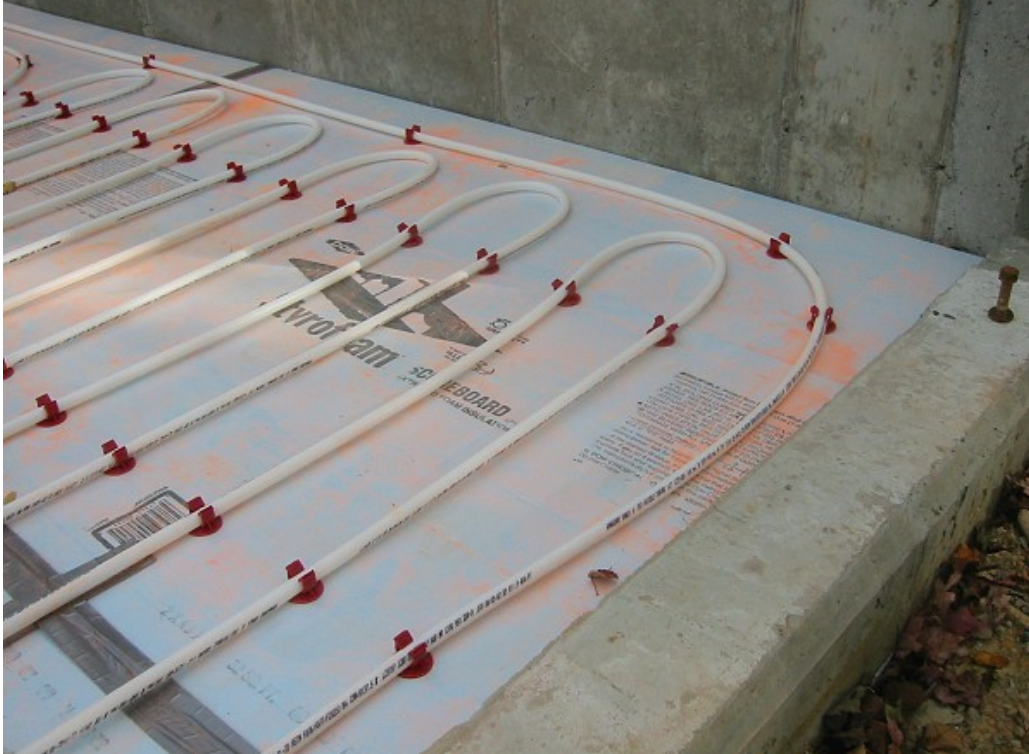
Radiant panels can supply or remove heat. The panels are almost always heated or cooled by water, occasionally by air, and even more rarely by refrigerant. One might also use conduction through, for example, concrete to cool or warm soil.

Since the last three terminal units rely on room air rising or air falling past the heated or cooled element to move the air, the size of the element is related to the size of the temperature difference. Fan coil units use fans to force the air across the heated or cooled element and hence can be relatively small for a given energy supply/removal rate. Small elements that are highly heated (such as electric wires) can cover a small area and obviate the

need for a fan. The maximum temperature is usually governed by burn hazards (less than 60 °C or 140 °F), and minimum temperatures for cooling limited by condensation risks (typically cooling surface must be more than 10-15 °C or 50-55 °F). Convectors that use natural buoyancy to slowly move air past the heated or cooled surface will be physically larger than equivalent performance fan coil units. Radiant panels use small temperature differences and hence they require large areas. Radiant floor heating typically covers over 80% of the floor area and radiant ceiling cooling 30 to 80% of the ceiling.

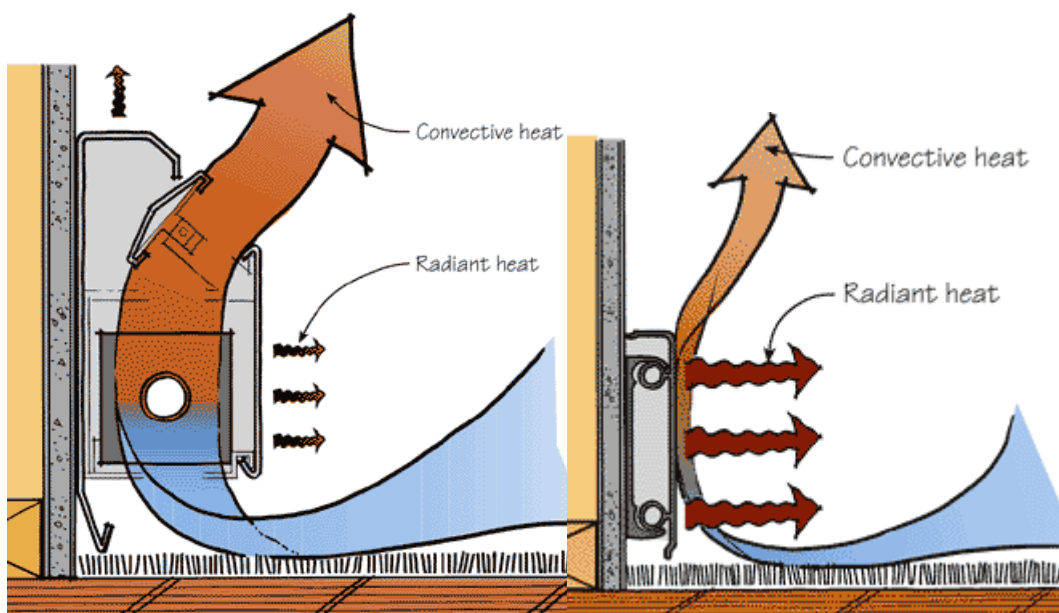


Radiant floor heating tubes over insulation



Radiant floor heating tubes in a basement

The higher the temperature difference at the terminal unit, the less fluid that needs to be moved to deliver or remove energy. The advantage of small temperature differences is a generally higher level of comfort and the ability to use more natural sources of energy (e.g., ground water can be circulated through ceiling mounted radiant cooling panels or solar heated water through radiant floors.). The energy cost of moving larger volumes of fluids is generally small.



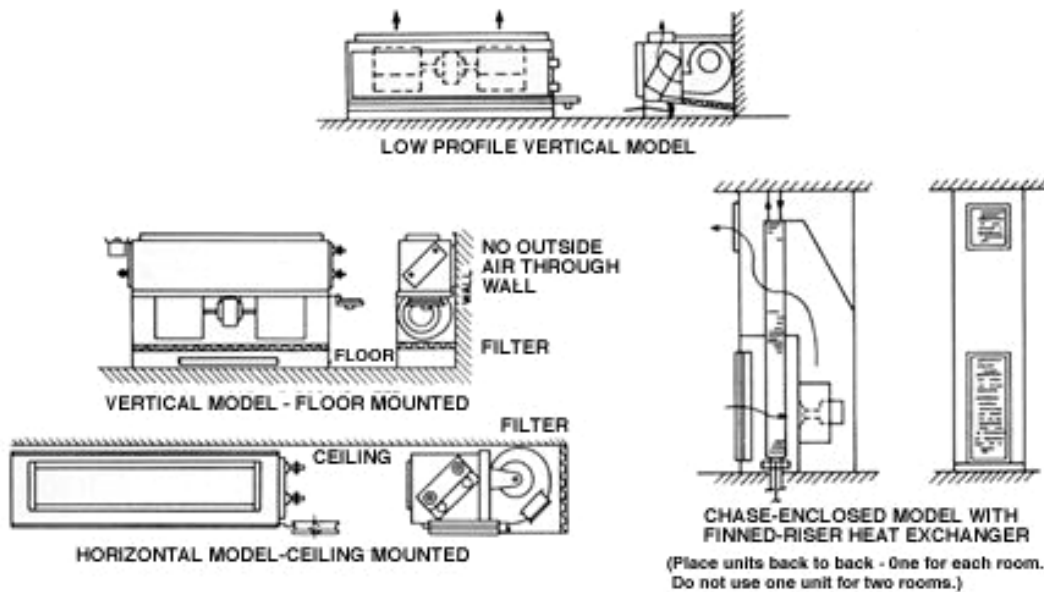
Typical convector-radiator cabinets mounted on a wall.



A commercial finned convector cabinet with cover removed and supply pipes visible



A hot water “radiator” terminal unit that actually transfers most of its heat to the room by convection



Typical Fan-Coil Unit Arrangements

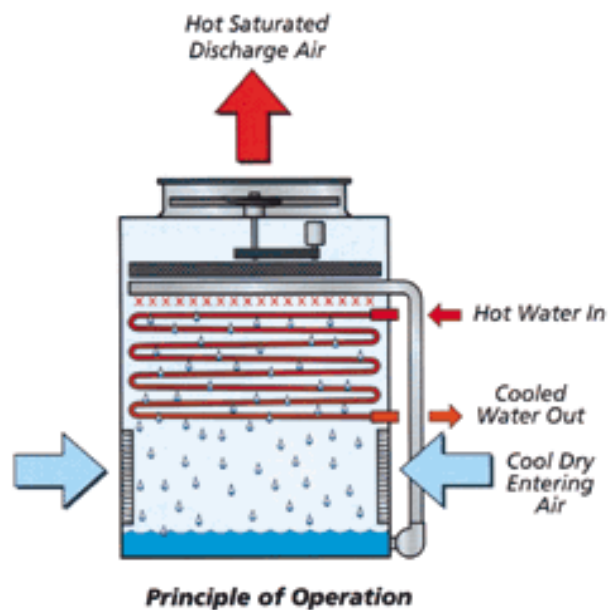
A fan-coil is a terminal unit that drives air past a finned tube containing hot or cold fluid. The air is usually drawn from the space to be conditioned and returned to it. They may be combined with filtration, often dehumidify (as humid air condenses on cold coils) and may mix untreated outdoor air into the stream. Often located at exterior walls below windows, they can also be installed in the floor or under the ceiling or within a suspended ceiling. They are rather efficient since they obviate the need to blow large quantities of air around a building, but do require decentralized maintenance (filter changes, condensate pan cleaning, etc.).

Heat Rejection Outside the building

Heat can be collected and is almost always (in buildings with cooling) rejected to the outside.

Evaporation of water sprayed through a cooling tower will reject heat to the outdoor air.

Rejection of heat to a stream of air flowing through a coil which contains warmer water or refrigerant or even air.



Cooling Tower Heat Rejection – hot water is cooled by spraying through outdoor air.



A more common shape of a cooling tower



A cooling Tower for a Large Cooling Load



A pair of DX heat rejection devices (note refrigerant lines) for small loads



A Primary Terminal Air Conditioning (PTAC) unit in a hotel room – a heat pump combined with a fan coil unit and outdoor air supply (optional) A hybrid terminal unit might be considered a heat pump in the room. Electricity is supplied and heat is produced/removed and distributed in the room via one of the terminal units described above.



A typical detached home air conditioning heat rejection unit.

Heat Production

Heat is produced from primary sources by combustion, collected from local natural sources (especially solar energy), and converted from electricity.

Electricity can be used to create heat using resistance heaters (i.e., heat produced like toaster) or heat pumps.

Electrical resistance heaters are essentially 100% efficient, but recall that the production and distribution of electricity is between 25 and 40% efficient. Hence the total system efficiency of electric heat from coal or gas is less than 40%.

We increase the quality of heat through the use of heat pumps, which use electricity (or rarely gas) to move energy and thereby increase or concentrate the energy and thus increase the temperature of the working fluid. A heat pump can extract the little bit of heat energy in a large stream of cold air or water and increase the temperature of a second smaller stream of air or water. It requires 1 unit of electricity to move between 3 and 5 units of heat energy. This ratio is termed the Coefficient of Performance, COP, and hence varies from 3 to 5. This can be seen as an “efficiency” of between 300 and 500%. Since the electricity generation efficiency is around 25 to 40%, the total system efficiency of heat pumps will range from 75 to 200%. Hence, in systems with high COP, a heat pump uses less primary energy than combustion. However, in systems with a low COP (<3) and poor electricity system efficiency ($<35\%$), a heat pump would use more energy to produce heat than a high efficiency natural gas furnace. Some advanced commercially available ground-source heat pumps have a COP of over 7.



Distribution

Distribution of energy and mass is important from a macro community scale view and at a building and room specific scale.

Macro-scale distribution

The transportation of electricity across the national grid consumes some 5 to 10% of energy produced for example. The transport of gas, oil, coal and biomass also consumes considerable amounts of energy in leakage, pumps, compression, spillage, trains and trucks. These losses increase cost, and generate environmental damage over and above that of the consumption in a building. The inefficient conversion of fossil fuels to electricity and the transmission losses means that electricity is often a polluting form of energy that is the most costly – it should be used carefully and sparingly.

Building Distribution

Distribution of air, heat, and cooling may be a major capital and operating cost issue for moving energy (especially when cooling) depending on the approach taken.

There are two common means of moving energy within a building are

1. moving a hot or cold fluid, specifically as a
 - a. liquid (usually water or some water glycol mix)
 - b. gas (such as air), or
 - c. liquid or gaseous refrigerant that changes phase (as in air conditioning units), or
2. moving electricity (which can only produce heat without additional equipment).

Each mode of transport can deliver heat to a space or remove it (through the use of a heat collection or rejection device) depending on system design and operation.



This photo shows chilled water lines (insulated with white vapor barrier covered insulation) leading into an above ceiling air handling unit in which a water to air heat exchanger (a finned tube) transfers the heat to air which is then distributed by ducts and driven by fans to diffusers that deliver the cooling required. The unit is covered with insulation and alu-foil vapor barrier to prevent surface condensation when warm humid summer air enters the building and finds its way above the suspended ceiling.



Service (power, communications fire suppression water) distribution in corridor of an apartment building



A view of a finned coil heat exchanger within a residential cooling system. It contains refrigerant that boils away at about 5 C / 40 F and takes heat with it.

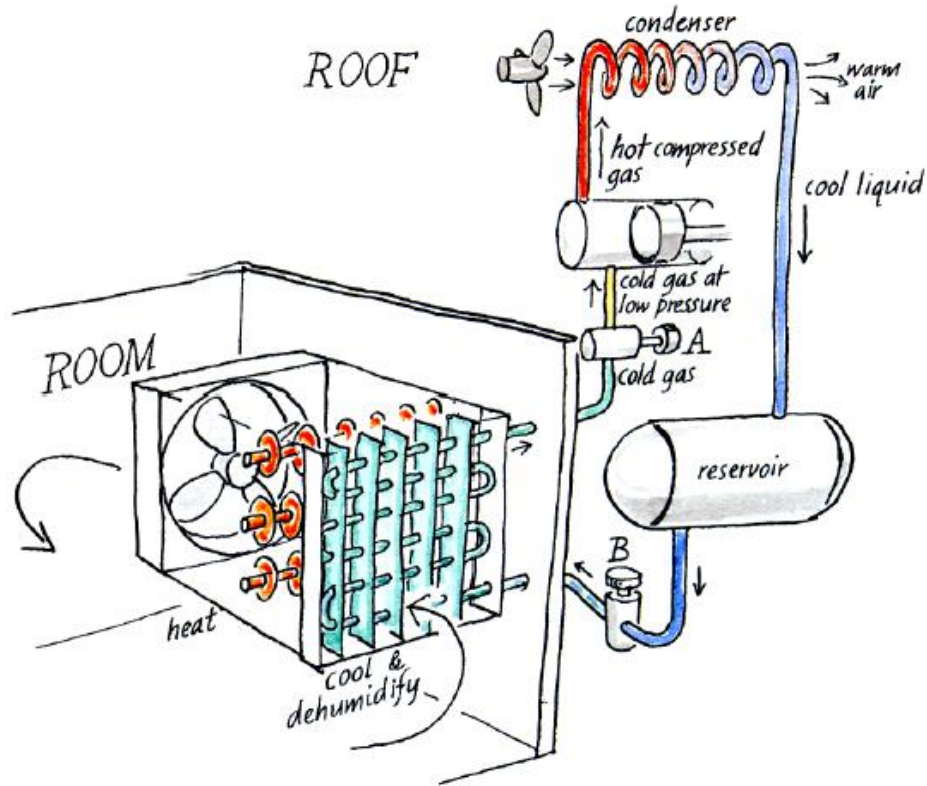
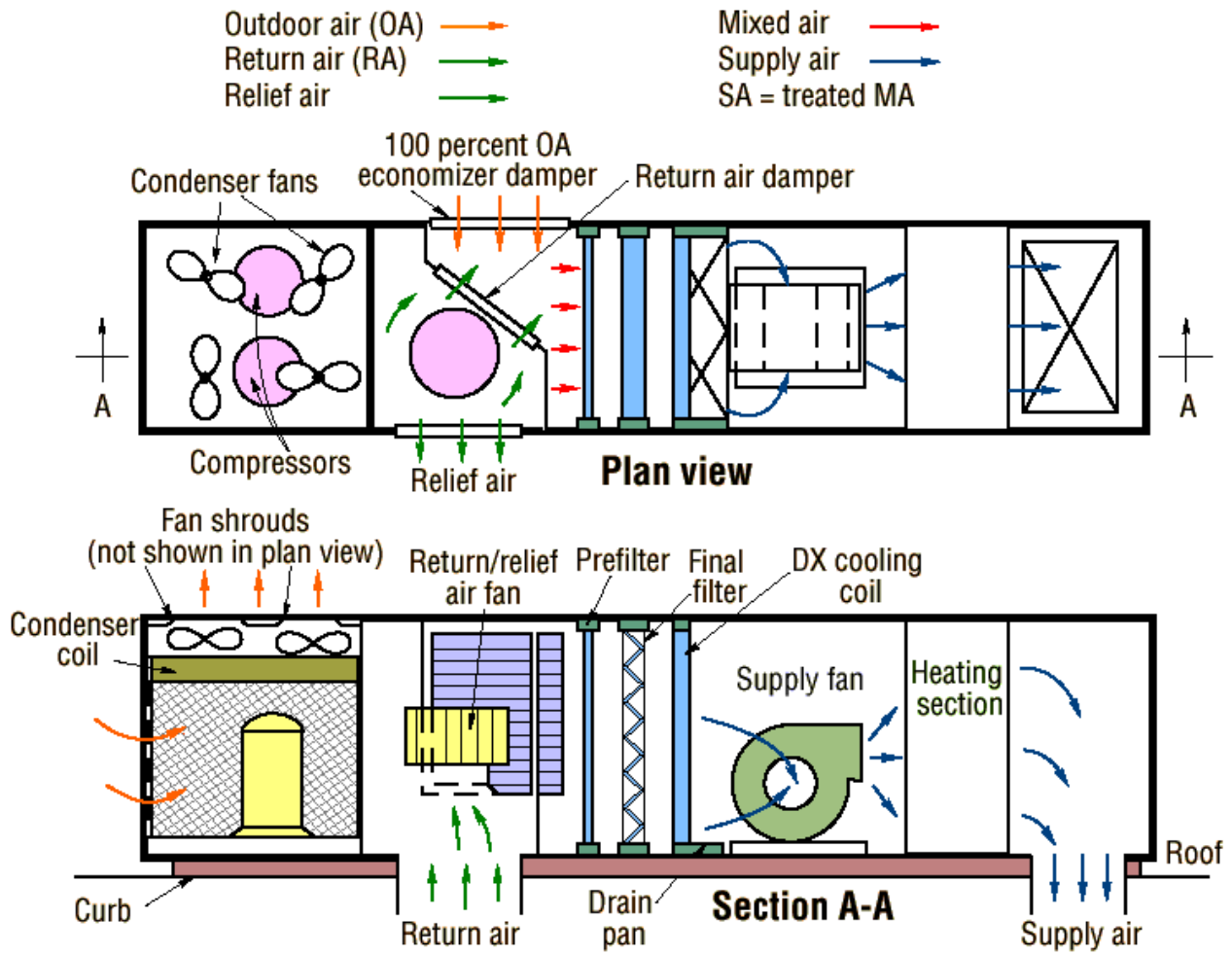


Figure 2. Minimal air conditioning. The part of the system in the room, on the left, pulls air first over a cool surface and then over a warming surface. The part of the system on the right recirculates the cooling fluid. The fluid passes from the reservoir through a valve **B** into the lower pressure within the cooling unit in the room. There the liquid boils, removing heat from the air. The boiling point is fixed by the constant pressure set by valve **A**. The vapour is then compressed and condensed back into a liquid which collects in the reservoir ready for another cycle.

Tim Padfield's drawing of how a heat pump (shown operating as a cooler, but both directions are possible)



1 Air-cooled DX rooftop package (not to scale).



Rooftop packaged units contain heating, cooling, filtration, and fresh air ventilation in one unit.



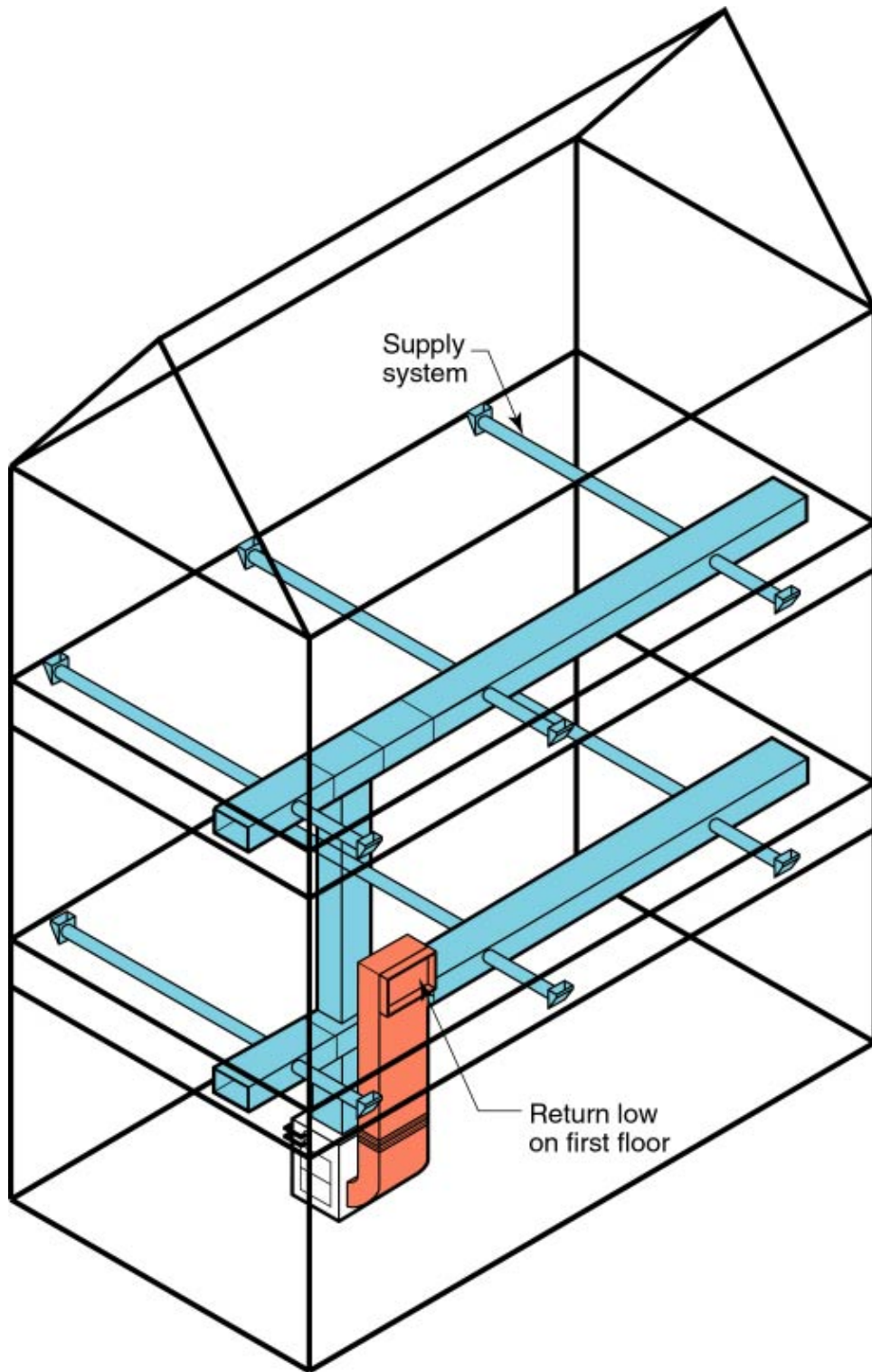
Ductless Split Systems use a refrigerant, not air, to transfer heat and cool.



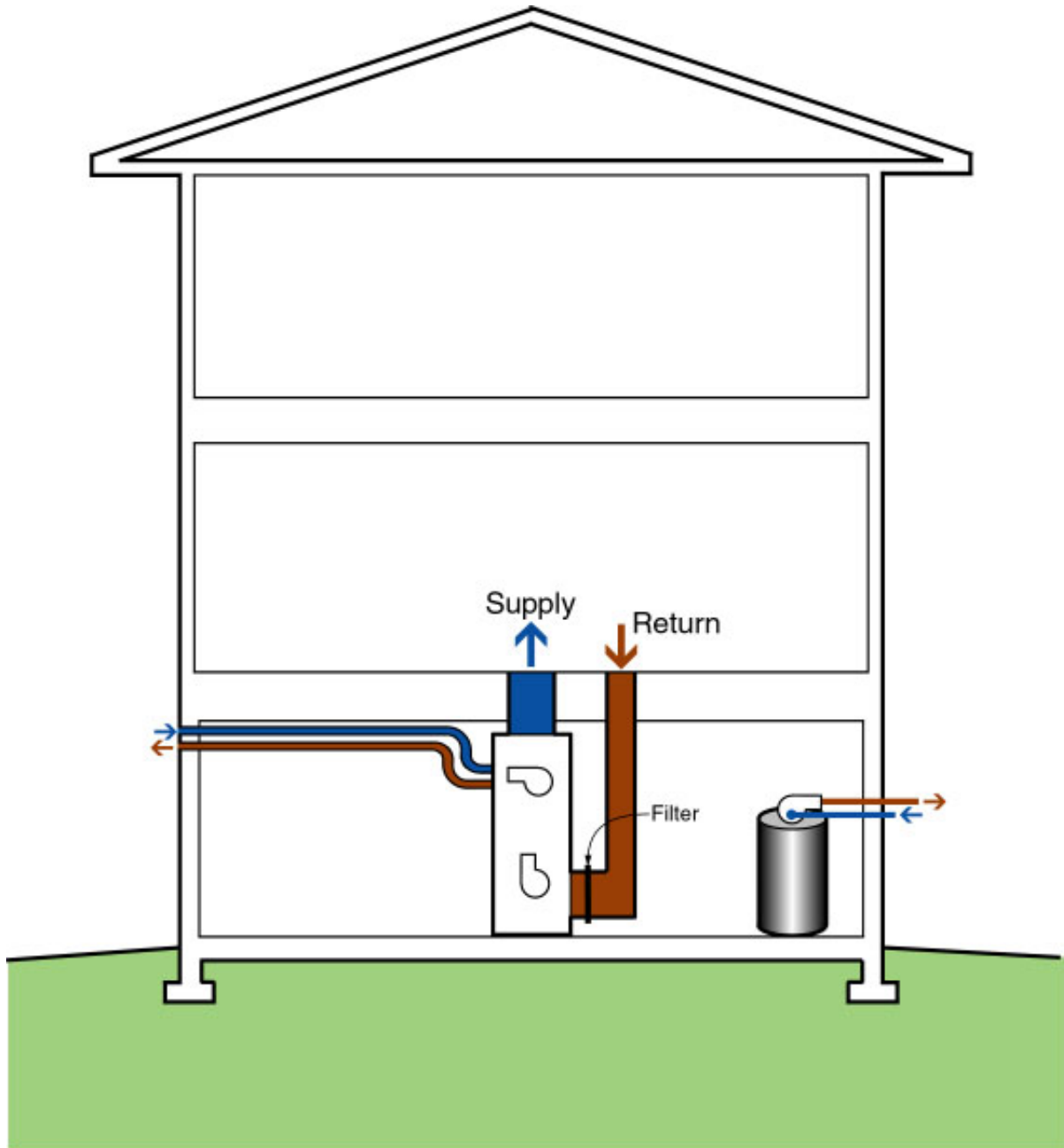
Outdoor Condenser Units



Indoor Ceiling Mounted unit

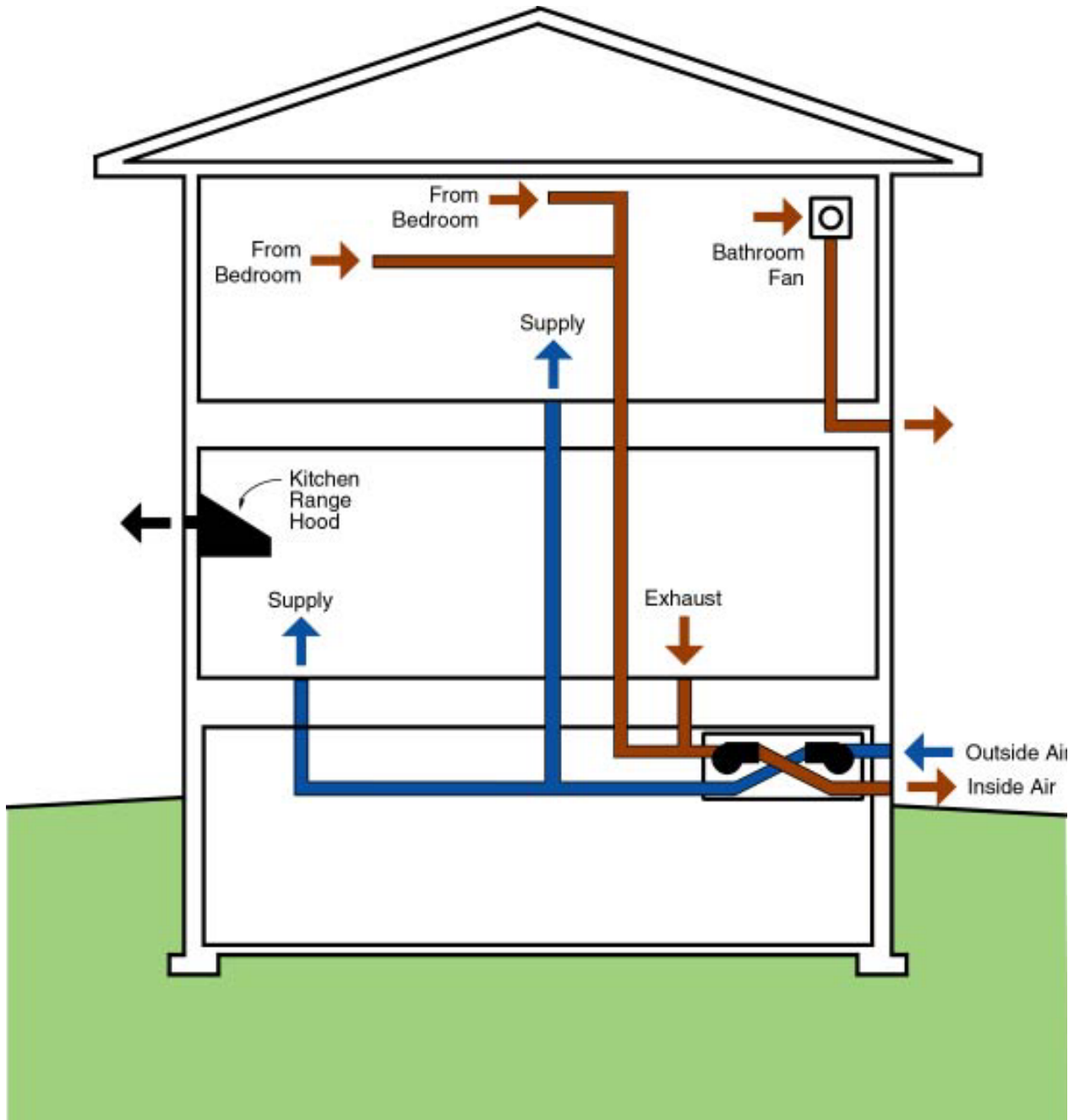


Courtesy of Building Science Corp
Air based distribution of heating, cooling and fresh air is typically delivered by a system of ductwork such as above.



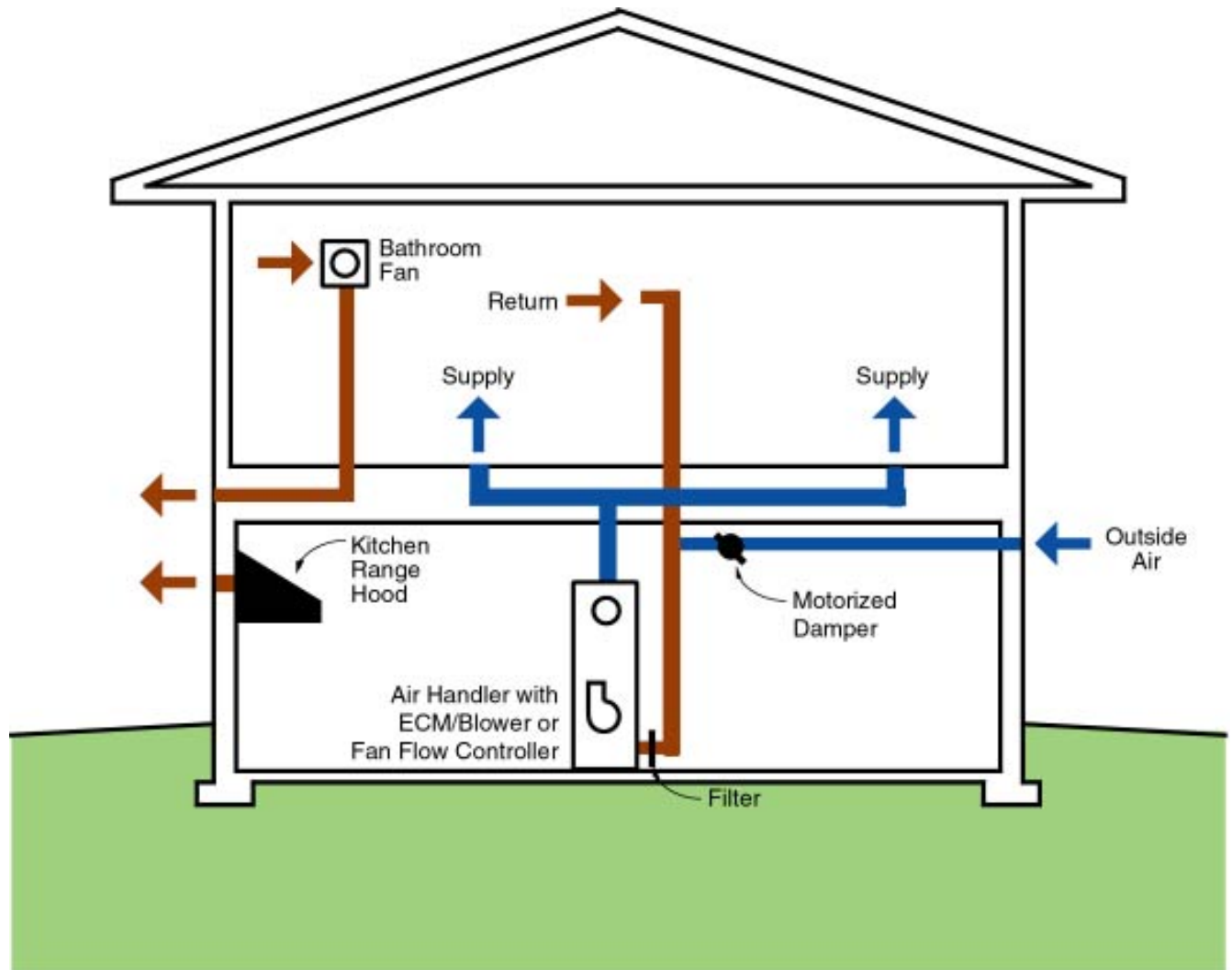
Courtesy of Building Science Corp

A closed combustion system of delivering heating and domestic hot water. The air required for combustion and the exhaust gases are ducted to the exterior as they should be.



Courtesy of Building Science Corp

A complete fresh air ventilation system for a house. This shows the optional heat exchange (heat recovery ventilator). The air can be simply exhausted and supplied at greater operational cost and lower capital.



Courtesy of Building Science Corp

A complete fresh air ventilation system for a house. A coil in the air handler can be used to heat or cool the air, and the filter cleans the air. Fresh air is provided via the outdoor duct, and a special controller operates the fan intermittently to provide sufficient fresh air.



It's a wonderful, wonderful feeling

to come home to cool comfort when it's steaming in the street outside. It's a pleasure *you* can enjoy with this beautiful new Carrier Room Air Conditioner. Day after day, it makes any room a refreshing haven, bringing in cooled, cleaned, filtered air . . . circulating it gently . . . and expelling stale, stuffy air. Men who know air conditioning best made it

simple to operate, quiet and easy to install—with more comfort per \$ than any comparable investment. Six new models—window and console—for different space requirements of home or office. May be finished in any color, custom-matched to your sample. Your Carrier dealer is listed in the Classified Telephone Directory. Don't wait for a heat wave—call him today! Carrier Corporation, Syracuse, N. Y.

AIR CONDITIONING **Carrier** REFRIGERATION

"Mention the National Geographic—It identifies you"

An ad from 1950 heralding the arrival of the wonder of residential scale air conditioning.

The energy consumed moving fluids around a large building are significant, whereas the energy required for a small and simple house is small. The energy used by fans to move air through a typical office building using a VAV system (more on this common type of system later) can consume 50% of the total energy during times of peak cooling. A similar system using water to transport heating and cooling energy can consume 1/3 to 1/2 as much energy.[see Kavanaugh, S., “Fan Demand and Energy”, ASHRAE Journal, June 2000, pp. 47-52.]

The most common way of moving heat energy outside North America is through the use of water. Water is non-toxic, widely available, and has one of the highest heat capacities of all room temperature fluids.

Airflow is the most common means of distributing energy in North American buildings. Air is easy to handle, and small leaks cause no problems (unfortunately it has recently become clear that leaky ducts can cause some serious building and human health problems). The major drawback of using air as a heat transfer fluid is its very low heat capacity. For the same temperature difference and same energy transport rate, one must move a volume of air 3 500 times larger than if water were used. This huge difference explains why a 25 mm (1”) diameter pipe of hot water can deliver more heating or cooling capacity around a building than a duct 450 x 300 mm (18 x 12”), even though the air is moving much faster in the duct than the water in the pipe. The implications for architectural-mechanical coordination and floor-to-floor height should be clear. This difference in heat capacity also means that a significantly greater amount of energy is required to *move* the energy.

A liter (quart) of water has the capacity to store 4.2 kJ for each degree Celsius temperature difference. Hence, a flow of one liter of water per second would move 4.2 kJ/second or 4.2 kW if there was only a one Celsius temperature drop. If the temperature drop were to be 10 C, 42 kW could be delivered, more than enough energy to heat a full sized house in very cold weather.

Within a building electricity distribution causes few losses and is generally easy to integrate into the architecture. Flat cables can be used under carpets but they do have their problems. If economical to do so, consider places wires in tubes or conduit to allow future replacement and upgrading.

General Rule: If you can expose the distribution system (eg if it is clean, orderly, ducted returns etc) then you can cover it up. If you cant (plenum returns, disorder, complexity) then you should not cover it.

Ventilation

The rate of ventilation is governed by the need to remove indoor pollutants (odour, chemical off gassing, and moisture), not to provide oxygen to replace that consumed. The ventilation rate required to meet the former need (termed dilution ventilation) depends on the production rate of pollutants, the use of other removal means (such as submarine’s recirculating mechanical systems with charcoal or chemical scrubbers), and social values of comfort. Ventilation rates vary from as little as 2 liter per second per person to as much as

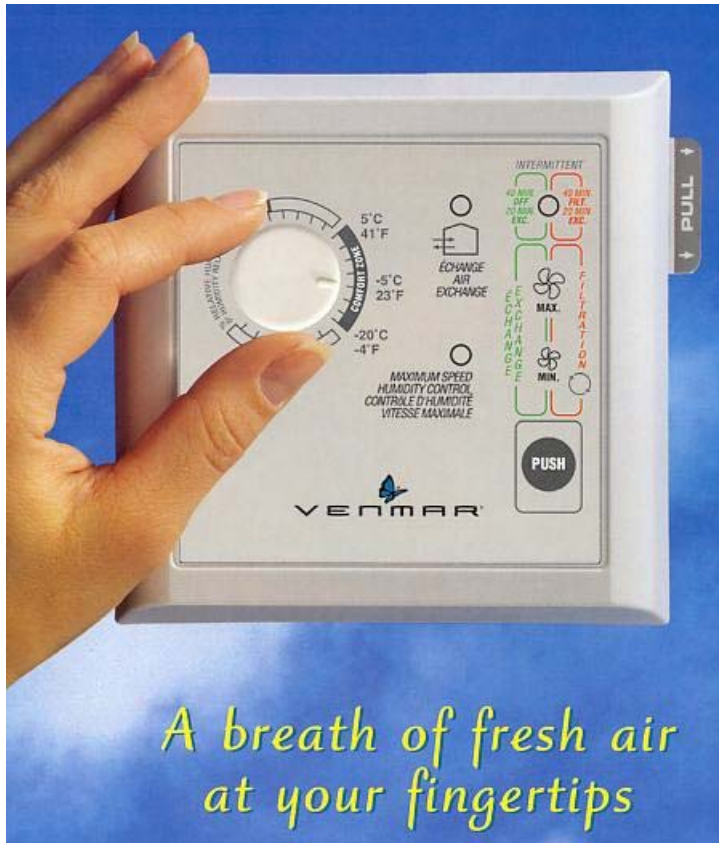
25 lps/person. Common usage in North American buildings is about 7.5 lps/person. This rate is probably much higher than needed, but accounts for typically poor ventilation mixing efficiency (the distribution within a conditioned space of the fresh air) and ventilation systems combined with heating and cooling. The use of direct to the face fresh air supply diffusers on airplanes and modern airplanes allows for much lower rates with no loss in efficacy.

Ventilation can be provided by mechanical means (common because it provides a guaranteed rate of flow) or natural forces (difficult to achieve because of the detailed design and analysis required).

Over ventilation is a problem because it consumes significant amounts of energy to condition the air (dehumidify, heat or cool) before supplying it to a space, especially in well insulated buildings with high occupancy. As much as 50% of the space conditioning load of a modern classroom can be due to ventilation air. The energy cost of ventilation can be significantly reduced (by a factor of three or four) through the use of air-to-air heat exchangers in the ventilation systems. These Heat Recovery Ventilators (HRVs) use the heat in the exhaust/stale air to heat the incoming cold fresh air. The reverse occurs in summer. Enthalpy Recovery Ventilators (ERVs) or Total Energy Recovery units also transfer the humidity in the two air streams – this can provide a very significant saving when air conditioning a building. If the building requires a significant amount of ventilation, heat or enthalpy recovery is almost always economically justified, and the first cost of the unit can often be saved in the reduced cost of smaller heating and/or cooling equipment, leaving operating cost reductions as a pure benefit.

Ventilation systems (sometimes called fresh air systems) are often combined with heating or cooling systems in North American buildings. This combination creates a number of challenges for delivering fresh air – in many systems (especially houses) the airflow system only operates on a call for cooling or heating. Hence, no ventilation is provided if the thermostat does not call for heating or cooling, or over ventilation occurs if the heating/cooling operates for extended periods. In other systems, ventilation is provided along with recirculated indoor air (at a ratio of about 5:1). This common approach means that pollution from one source in a building is distributed throughout a building by the air distribution system and only diluted by 20% in each pass.

There is a resurgence in interest in dedicated ventilation systems to provide the best air quality and reduce energy consumption. In large buildings, this approach is called the Direct Outdoor Air Systems (DOAS).



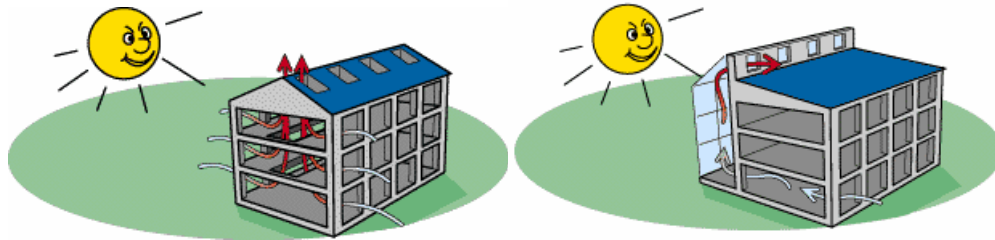
Ventilation systems, with or without heat recovery, are used to provide fresh air, and can be used to reduce interior relative humidity when it is cold outside.



A 15 year old HRV with cover open – note diamond shaped heat exchange core, dual fans (on right side) and insulated ducts for supply and exhaust to exterior



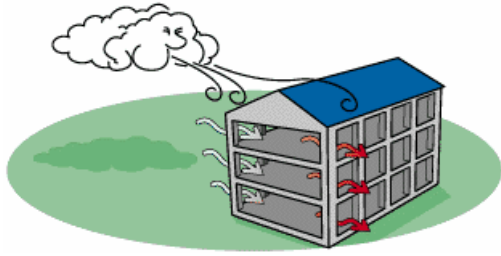
The most common naturally ventilated buildings in Canada – Livestock barns (in this case a dairy barn).



Stack effect (hot air rising) can drive air flow up and out of a building

Solar-assisted stack effect natural ventilation – since it uses the buoyancy of warm air to drive flow it only works when the greenhouse/atrium or building air is warmer, usually by at least 5 C, than the exterior air. Hence, this approach cannot work if the temperature outdoors is near the interior conditions, i.e., during warm weather.

To provide solar driven ventilation without overheating the interior space in summer, solar chimneys or stacks, thermally isolated from the interior can be used. These work well all year long of course. Ventilating a building in hot, and especially hot-humid weather is a major challenge, since the incoming air is warmer and more humid than desired. Hence, it should be cooled and dehumidified before supplying it to the occupied space. This is easily accomplished with compression based cooling equipment. Attempts to cool the air using thermal mass (especially when the air is drawn in through earth-coupled tubes or spaces) are usually the cause of summer mold problems within these spaces.



Wind



A British Window with a trickle ventilator at the head

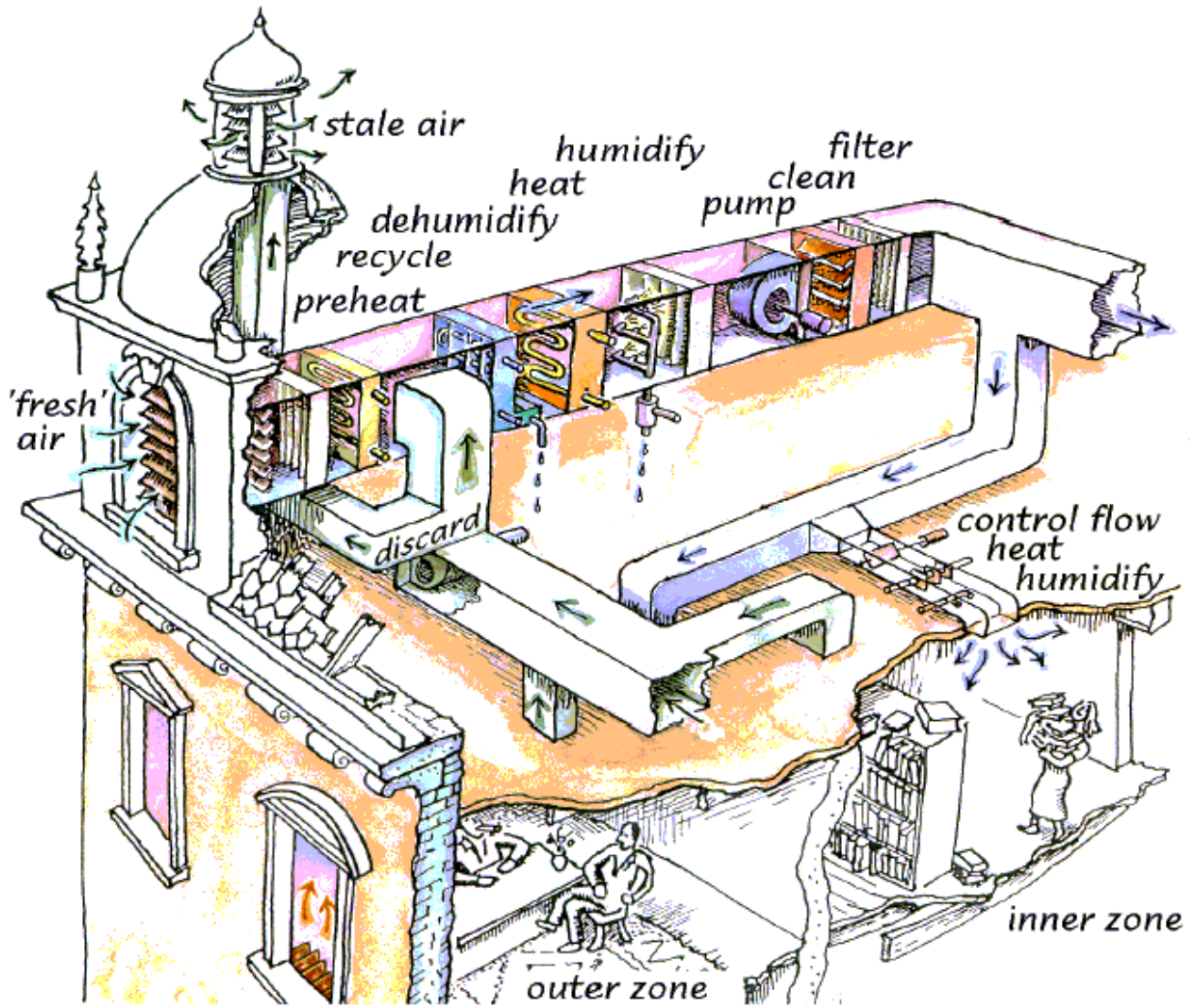
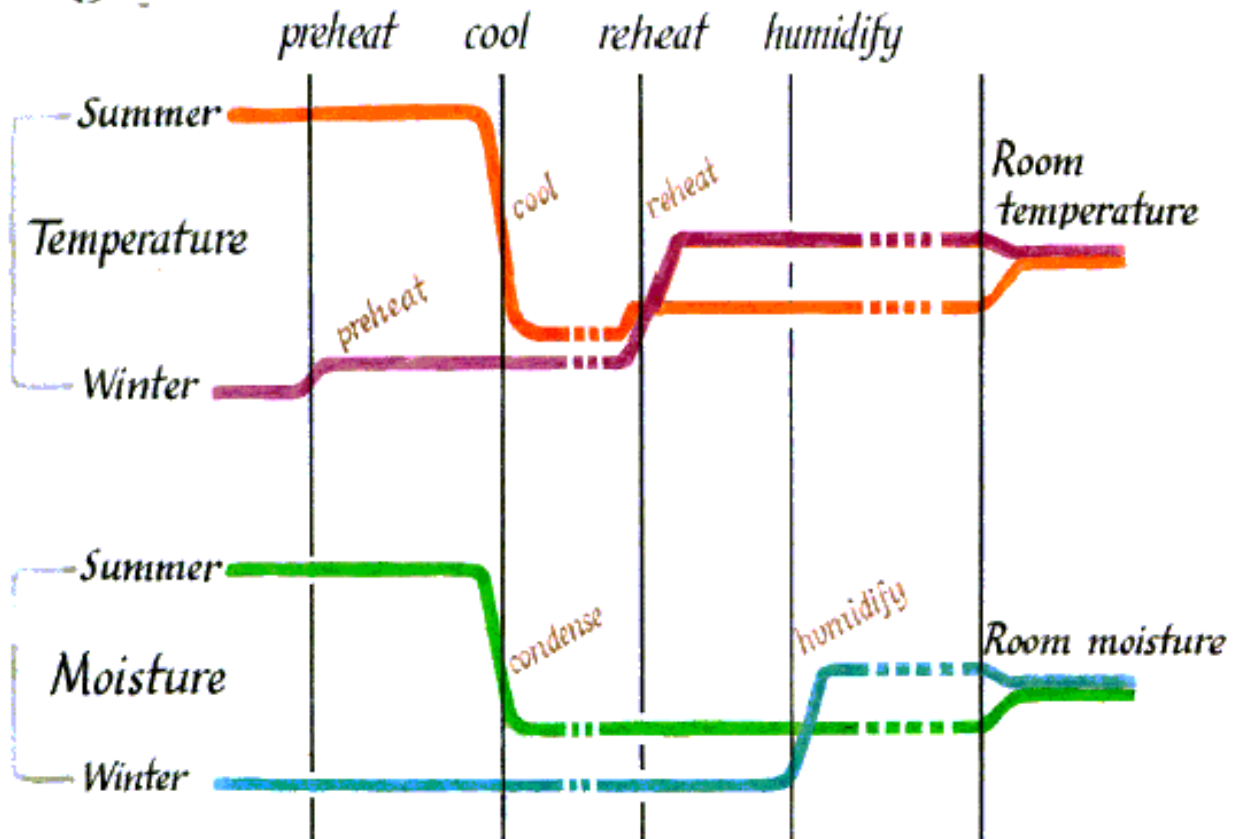
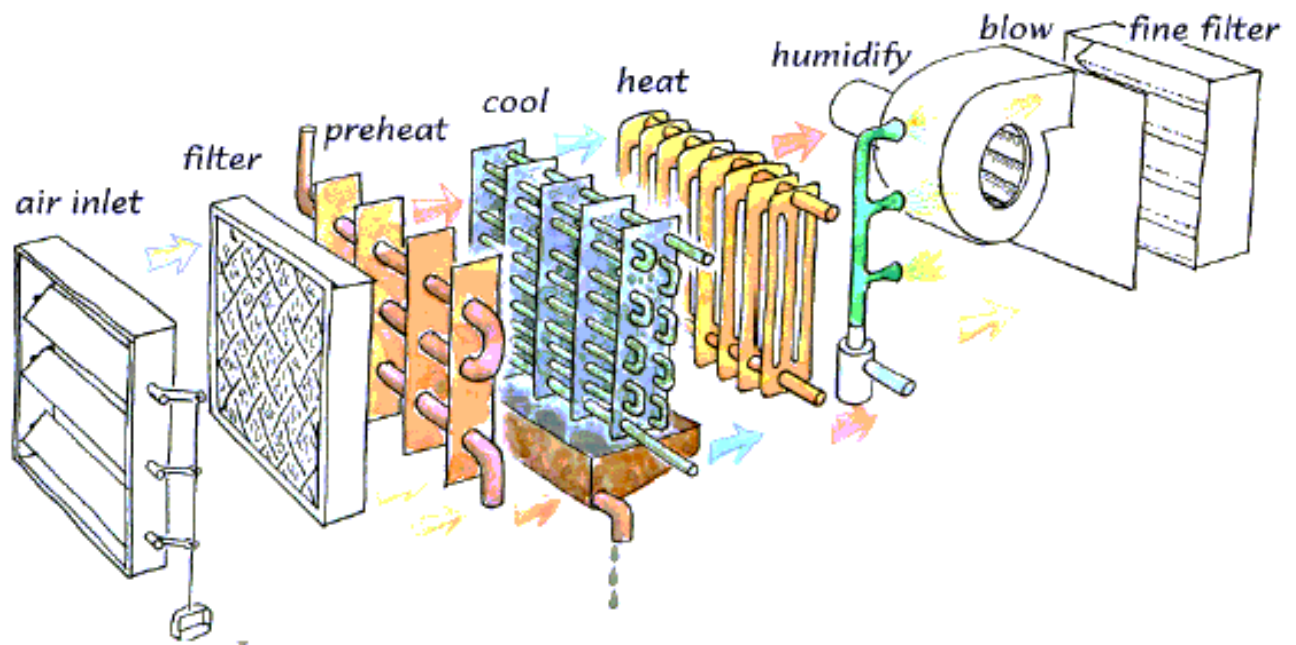


Figure 4. An air conditioning system with variable fresh air mixer and dust and pollutant filtration. Notice supplementary heating with radiators in the outer rooms and individual mini heater and humidifier in the air stream to each room.

Tim Padfield's drawing of how a typical modern air-based HVAC system works



A plot of how temperature and moisture content varies through a system in winter and summer