Explanation of the Limitation in the equipartition theorem

Imagine we have some He gas atoms in a box:

According to the way we've been thinking, when we add $Q$, it all goes to increasing the $k$ of these atoms.

However, what about the electrons within each atom? We know that the quantum levels for each atom look like this:

\[
\begin{align*}
3s & \\
2p & \\
2s & \\
\end{align*}
\]

\[
1s \rightarrow \text{ground state is occupied by two electrons for He.}
\]

If we could use some $Q$ to promote one of the electrons of each atom from $1s$ to $2s$, then there would be less $Q$ left to increase $k \rightarrow \Delta T$ would be smaller $\implies C$ would be bigger.

However, the energy difference between $1s$ & $2s$ is $\sim 10 \text{eV}$ (where $1 \text{eV} =$ the energy acquired by an electron as it moves through a voltage diff. of $1 \text{V}$; $1 \text{eV} = 1.6 \times 10^{-19} \text{J}$)

By comparison, $kBT \approx 0.026 \text{eV} \rightarrow$ there is not nearly enough thermal energy available to promote electrons in this way $\rightarrow$ this "degree of freedom" doesn't "count" toward $C$.

Similarly, in a solid the energy levels for the vibration of atoms are given by $E_n = (n + \frac{1}{2})\hbar\omega$.

As we cool the sample, $kBT$ gets smaller than $\hbar\omega$. So, it becomes less and less probable that we can thermally excite one of these oscillators out of the "ground state" ($n=0$) to an excited state ($n=1$, $2$, etc.) $\rightarrow$ as the sample gets colder, these "degrees of freedom" stop "count" toward $C \implies C$ goes down.

Heat transfer: Conduction, Convection, & Radiation

**Conduction**

\[
P = -k \frac{\Delta T}{\Delta x}
\]

$k \approx 0.1 \text{ W/mK}$ for electrical insulators

$n \approx 100$ for metals

**Units:** $1 \text{ft}^2 \cdot \text{OF} \cdot \text{s} / \text{Btu} = 0.571 \text{ m}^2 \cdot \text{KS} / \text{J}$

Multiple layers: just add $R$-factors
Convection: The transport of heat through the motion of a fluid. Much more complicated than conduction, varies a lot from one situation to another.

\[ P = h \Delta T \]

\( \Delta T \) = temp. difference between surface & surrounding fluid.

Air: \( h = 10 \) to \( 100 \frac{W}{m^2K} \)

driven by thermal differences (mechanically)

Water: \( h = 100 \) to \( 5000 \frac{W}{m^2K} \)

An object in thermal equilibrium with its surroundings absorbs the same power of radiation (from surroundings) as it emits (to surroundings).

\[ \Rightarrow \] A good absorber (something black) is also a good emitter.

Every piece of matter emits radiation; at room temp, the radiation is mostly at infrared wavelengths, so we can't see it.

Radiation

\[ P_{\text{emitted}} = \epsilon \sigma A T^4 \]

\( \sigma = \) Stefan-Boltzmann const.

\[ = 5.67 \times 10^{-8} \frac{W}{m^2K^4} \]

\( \epsilon = \) emissivity = 1 for perfect absorber

(perfectly black object)

= 0 for perfect reflector