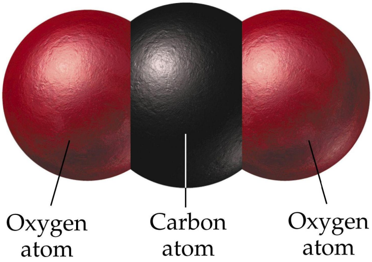
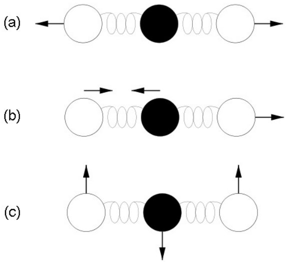
Why Is CO_2 a Greenhouse Gas?

The Earth is warming and the cause is the increase in greenhouse gases like carbon dioxide (CO_2) in the atmosphere. Carbon dioxide is a linear, triatomic molecule with a central carbon atom. The harmonic vibrations of CO_2 give it its absorption properties.

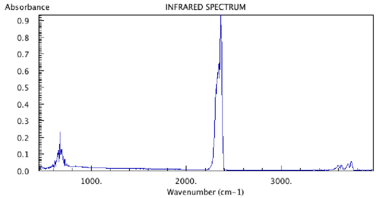


The vibrations of CO_2 can be described by a small set of 'normal modes' shown here. If a normal mode distorts the symmetry of the charge distribution of the molecule, then it will acquire an electric dipole moment and can absorb light in the infrared range - preventing that light from passing through the atmosphere.

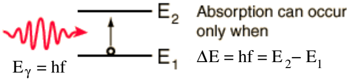


CO_2 Absorption Spectrum

The CO_2 absorption spectrum shown below has prominent absorption peaks at $k = 2350\ cm^{-1}$ and $k = 667\ cm^{-1}$.

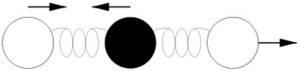


The peak is located at the frequency of light that is absorbed as the CO_2 molecule makes the transition from one quantized energy state to a higher one. The energy of the light is $E_\gamma = hf$ where h is Planck's constant.



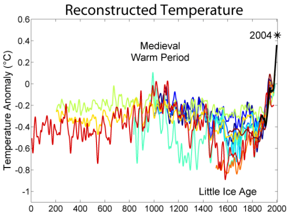
The atoms vibrate in the asymmetric mode shown here. This particular mode gives CO_2 some of its greenhouse gas properties.

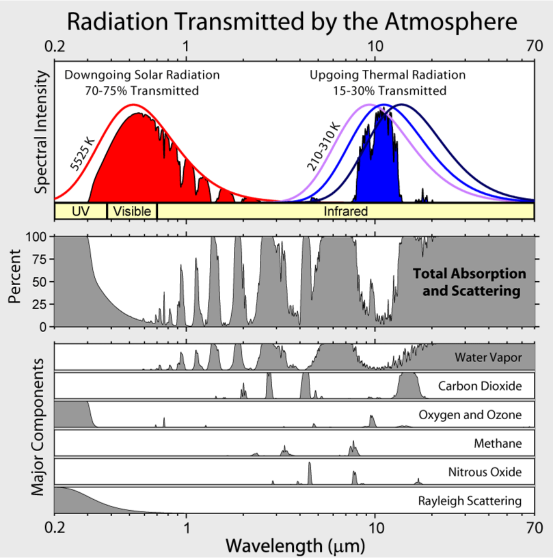
(b)



The figure to the right shows absorption bands in the atmosphere (middle panel) and the effect on both solar radiation and upgoing thermal radiation (top panel). Absorption spectrum for major greenhouse gases plus Rayleigh scattering are shown in the lower panel.

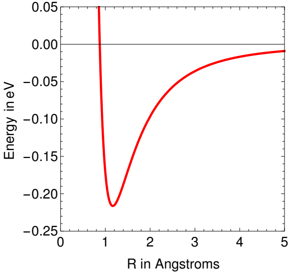
The surface temperature anomaly for the last two thousand years is shown below for measurements up to the year 2004.

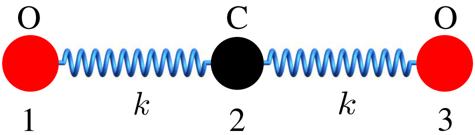




R. A. Rohde - `http://www.globalwarmingart.com/wiki/File:1000_Year_Temperature_Comparison.png`

Our picture of atomic motion in a molecule is built around classical ideas. Consider the CO_2 molecule below. The interactions of the atoms is described as point particles attached by springs. The spring constant for the $C-O$ bond is $7.0\ eV/Å^2$ derived from the $C-O$ bond potential shown below. Suppose our 'toy' CO_2 molecule is 'plucked' by pulling the left-hand-side oxygen atom 0.2 Å to the left and the right-hand-side oxygen 0.2 Å to the right. Both atoms are then released from rest. What is the position of each atom in the molecule as a function of time?

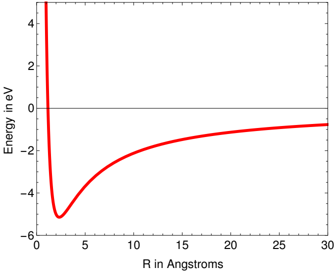


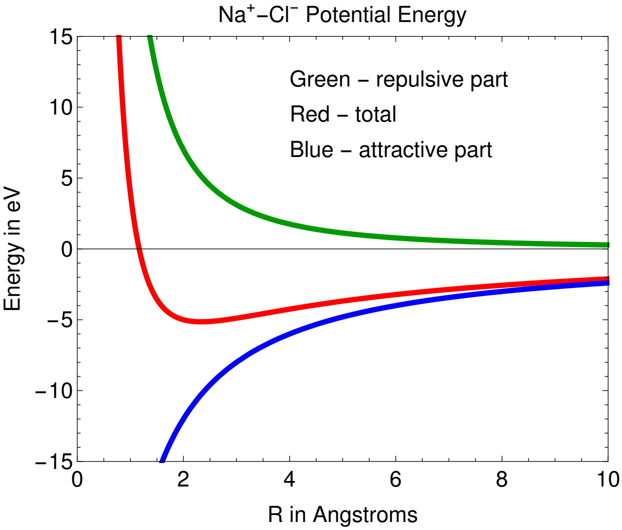


The potential energy between a Na^+ ion and a Cl^- ion is

$$V(r) = -\frac{A}{r} + \frac{B}{r^2}$$

where $\mathrm{A} = 24\ \mathrm{eV} - \mathrm{\AA}$ and $\mathrm{B} = 28\ \mathrm{eV} - \mathrm{\AA}^2$. Is the attractive part of V consistent with the force between two point charges? Where is the equilibrium point? What equation describes the ions' separation near the equilibrium point? What is the energy of the system? At $t = 0$, the separation of the ions is $2.0\ \mathrm{\AA}$ and their relative velocity is zero.

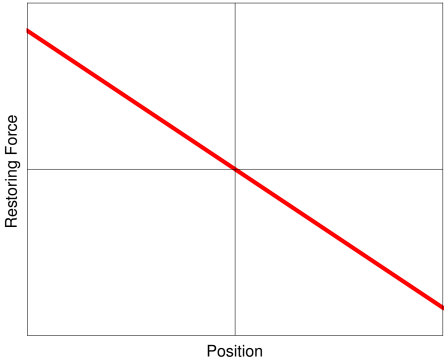


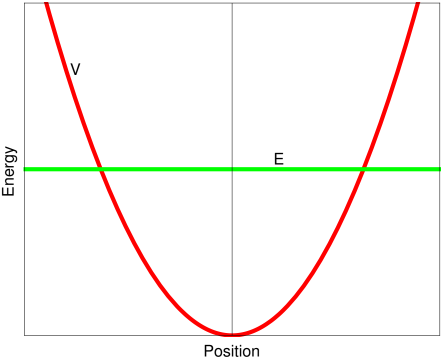


Na⁺–Cl⁻ Potential Energy
Green – repulsive part
Red – total
Blue – attractive part
Energy in eV
R in Angstroms
15
10
5
0
−5
−10
−15
0
2
4
6
8
10

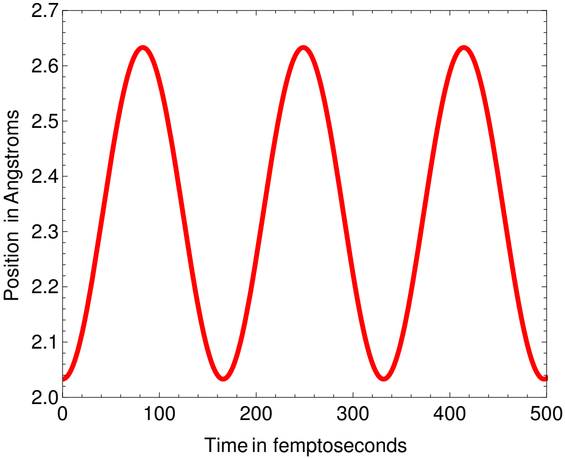
Recall Hooke's Law.

$$F_s = -kx \quad \longrightarrow \quad V_s = \frac{kx^2}{2}$$

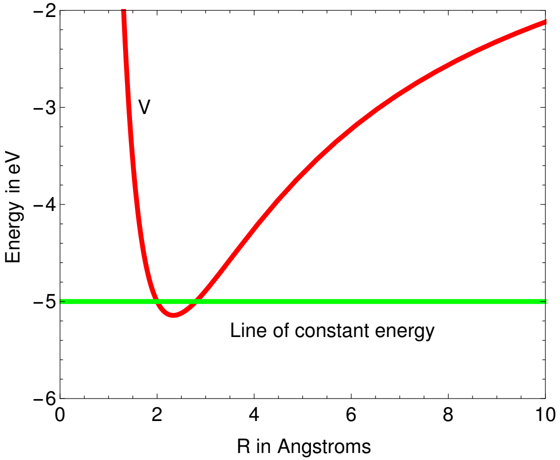




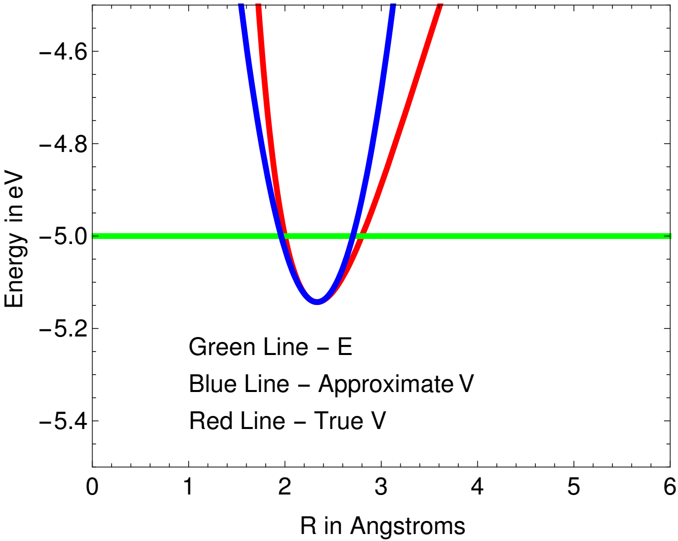
$Na^+ - Cl^-$ Separation



$Na^+ - Cl^-$ Potential



Closer Look At The $Na^+ - Cl^-$ Potential

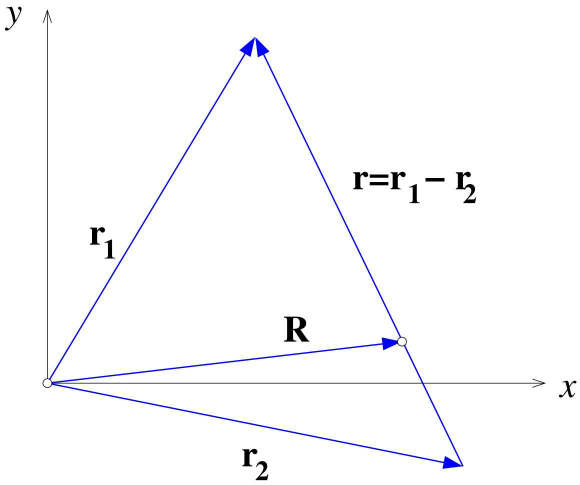


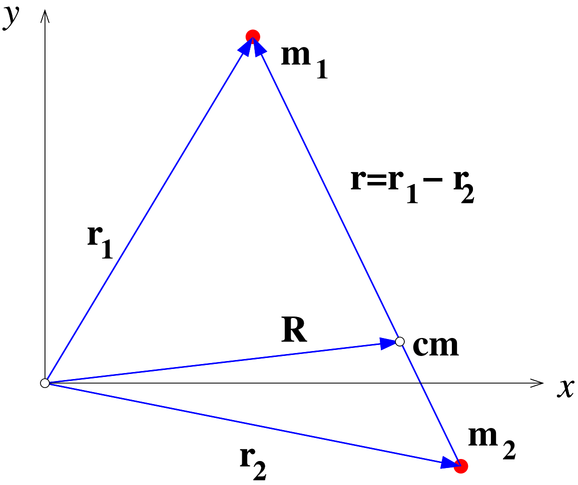
For two particles m_1 and m_2 interacting through some attractive force so they are bound we will use a particular coordinated system called the center-of-mass (CM) system. The CM of the two particles is

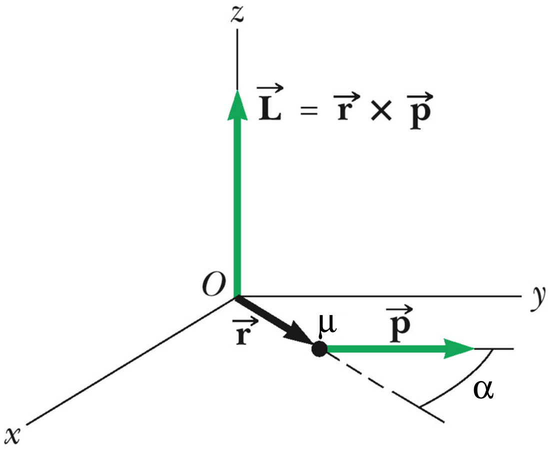
$$\vec{r}_{cm} = \frac{m_1 \vec{r}_1 + m_2 \vec{r}_2}{m_1 + m_2}$$

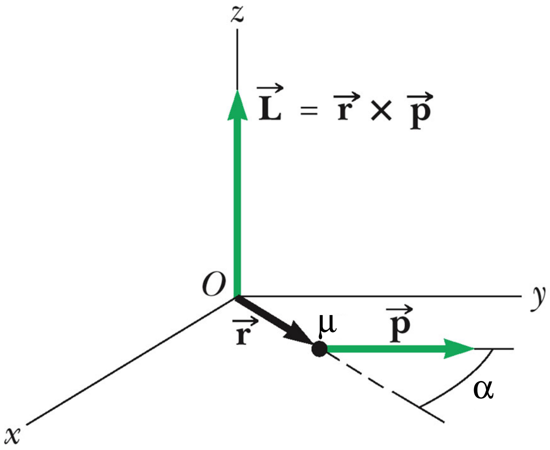
and it acts like this. The two particles in the system now behave as single particle with a different mass called the reduced mass.

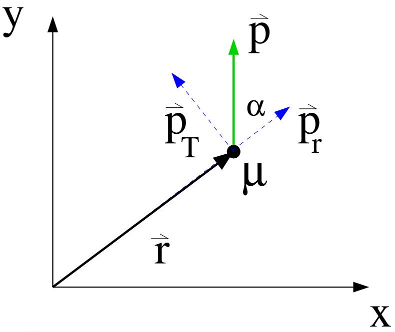
$$m_r = \frac{m_1 m_2}{m_1 + m_2}$$


y
x
r=r1 − r2
r1
R
r2


y
m 1
r=r 1 − r 2
r 1
R
cm
x
m 2
r 2


z
$\vec{L} = \vec{r} \times \vec{p}$
O
y
$\vec{r}$
μ
$\vec{p}$
α
x


z
$\vec{L} = \vec{r} \times \vec{p}$
O
y
$\vec{r}$
μ
$\vec{p}$
α
x


y
$\vec{p}$
α
$\vec{p}_T$
$\vec{p}_r$
μ
$\vec{r}$
x

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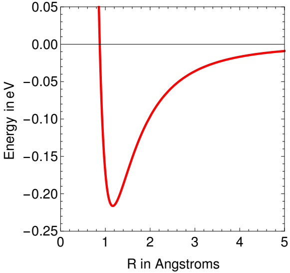
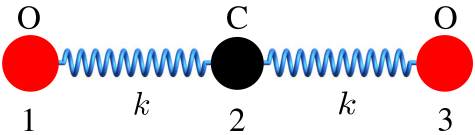
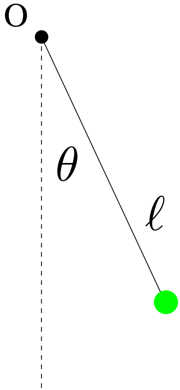
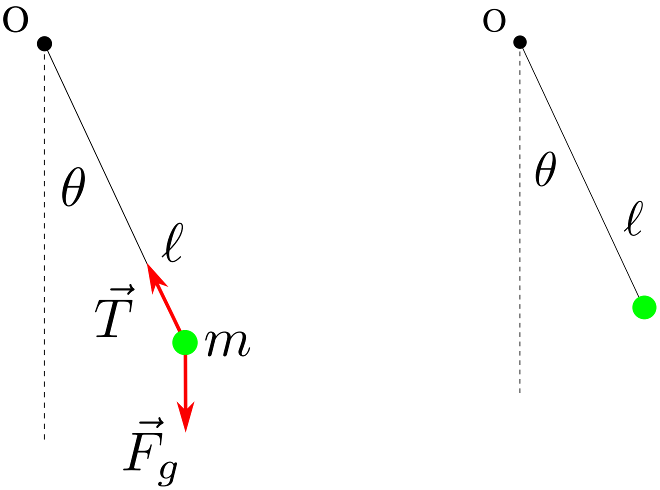
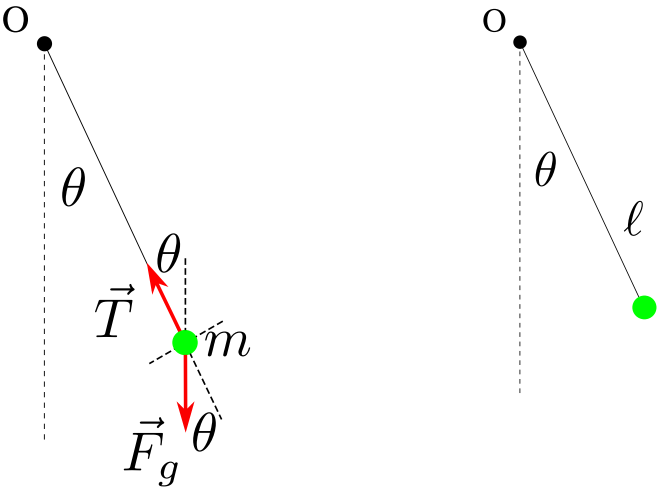


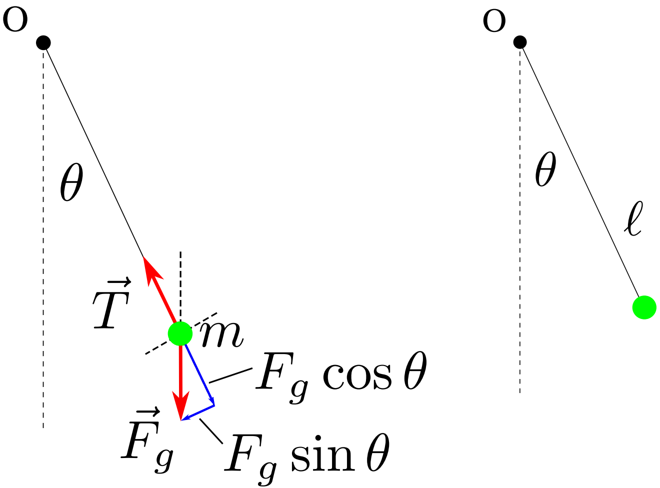


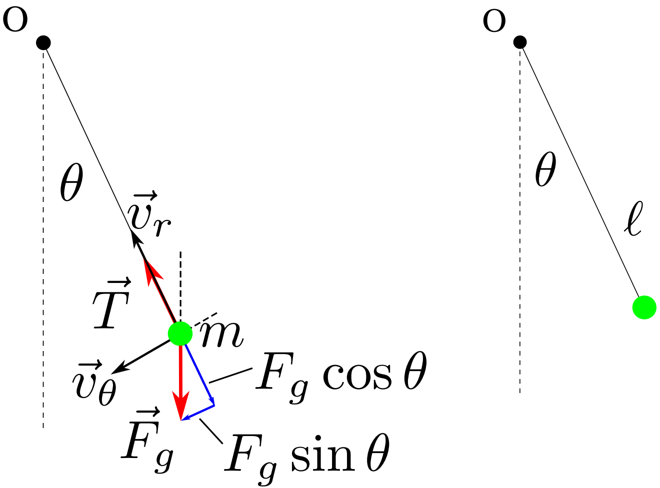
Consider the simple pendulum shown in the figure below. Find the position of the pendulum 'bob' as a function of time when the bob is pulled back through an angle of θ_0 with the string taut and released from rest. The initial angle θ_0 is small. The length of the string is ℓ.

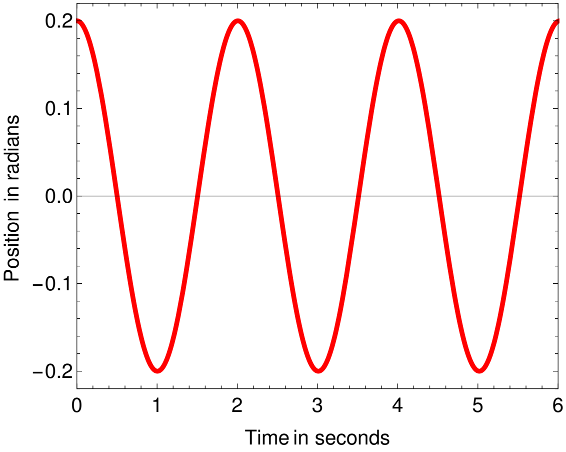



O
θ
ℓ
$\vec{T}$
m
$\vec{F}_g$
O
θ
ℓ


O
θ
θ
$\vec{T}$
m
$\vec{F}_g$
θ
O
θ
ℓ

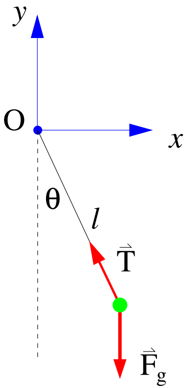

O
θ
$\vec{T}$
m
$F_g \cos\theta$
$\vec{F}_g$
$F_g \sin\theta$
O
θ
ℓ


O
θ
$\vec{v}_r$
$\vec{T}$
m
$\vec{v}_\theta$
$F_g \cos\theta$
$\vec{F}_g$
$F_g \sin\theta$
O
θ
ℓ



$$\ell = 1.0\ m \qquad \text{and} \qquad \theta_0 = 0.2\ rad$$

Consider the simple pendulum shown in the figure below. What is the Lagrangian? Find the position of the pendulum 'bob' as a function of time. The initial angle θ_0 is small. The length of the string is ℓ.



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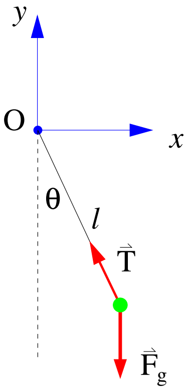

$$\ddot{\theta} + \omega_0^2 \theta = 0$$

$$\theta = A \cos(\omega_o t + \phi)$$

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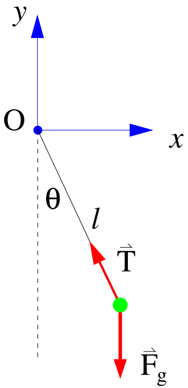

$$\ddot{\theta} + \omega_0^2 \theta = 0$$

$$\theta = A\cos(\omega_o t + \phi)$$

$$x = r\sin\theta$$

$$y = -r\cos\theta$$

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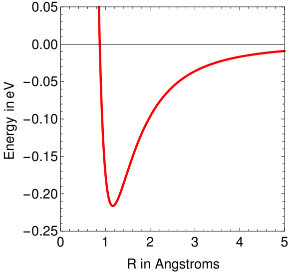
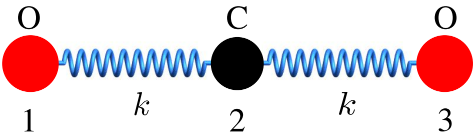
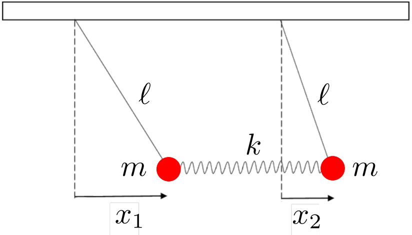




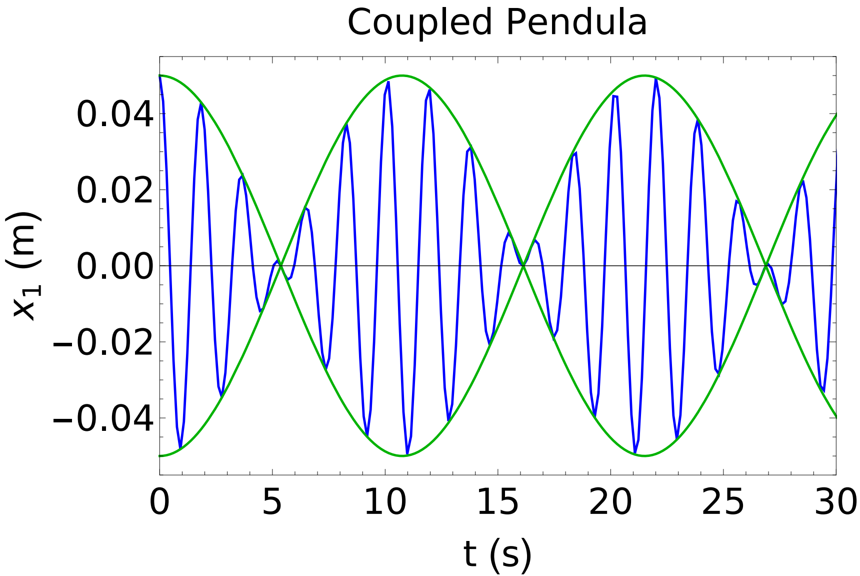
Before studying the more-complicated vibrations of the $\mathrm{CO_2}$ molecule consider the following problem. Two simple, identical pendula of mass m each are suspended on strings of length ℓ and connected to each other by a spring of spring constant k. The horizontal displacements from the equilibrium positions are x_1 and x_2 as shown. An example is here.

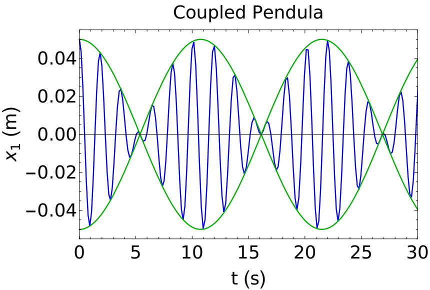


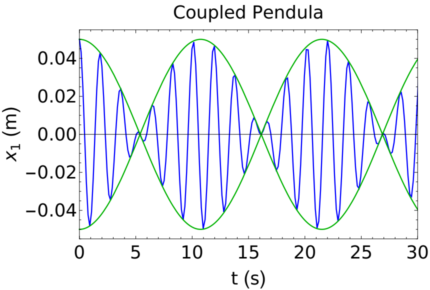
$\ell = 1.0\ m$
$k = 2.0\ N/m$
$m = 1.0\ kg$

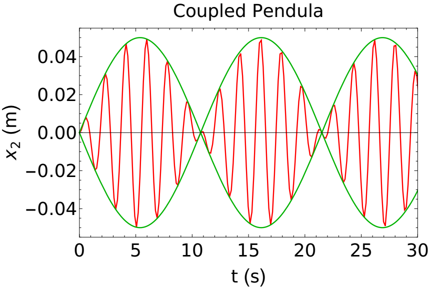
If the left-hand pendulum is plucked, then what is the position of each pendulum as a function of time. In other words, the initial conditions are the following.

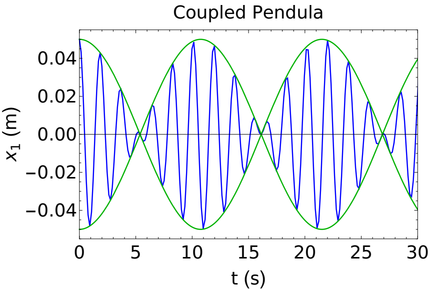
$$x_1(0) = d = 0.05\ m \qquad \dot{x}_1(0) = 0 \qquad x_2(0) = 0 \qquad \dot{x}_2(0) = 0$$

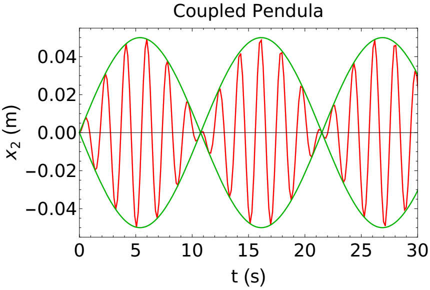

Coupled Pendula
0.04
0.02
0.00
−0.02
−0.04
x_1 (m)
0
5
10
15
20
25
30
t (s)

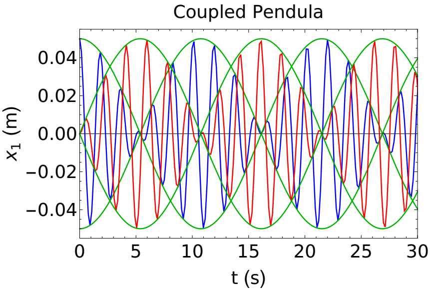

Coupled Pendula
0.04
0.02
0.00
−0.02
−0.04
x_1 (m)
0
5
10
15
20
25
30
t (s)


Coupled Pendula
0.04
0.02
0.00
−0.02
−0.04
x_1 (m)
0
5
10
15
20
25
30
t (s)


Coupled Pendula
0.04
0.02
0.00
−0.02
−0.04
x_2 (m)
0
5
10
15
20
25
30
t (s)

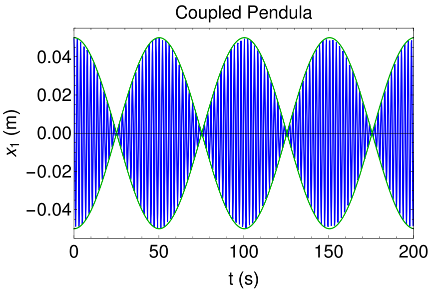

Coupled Pendula
0.04
0.02
0.00
−0.02
−0.04
x_1 (m)
0 5 10 15 20 25 30
t (s)


Coupled Pendula
0.04
0.02
0.00
−0.02
−0.04
x_2 (m)
0 5 10 15 20 25 30
t (s)

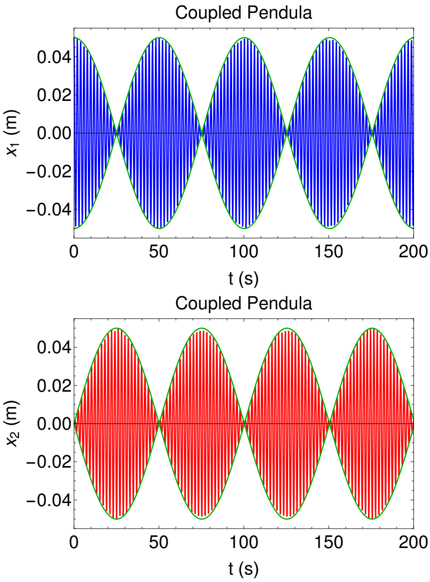

Coupled Pendula
0.04
0.02
0.00
−0.02
−0.04
x_1 (m)
0 5 10 15 20 25 30
t (s)

Click here.

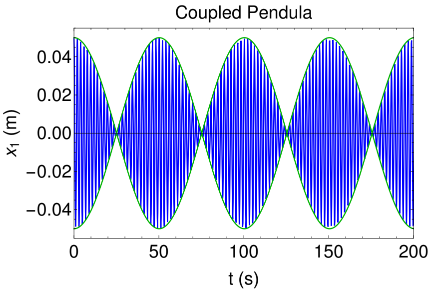
And Go Faster

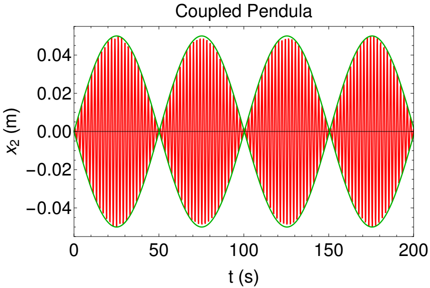


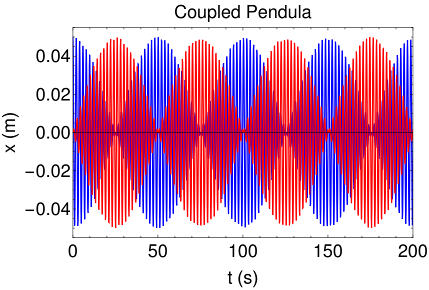
And Go Faster



And Go Faster







Click here.

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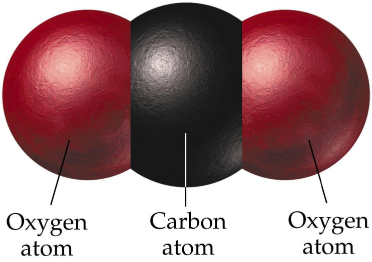

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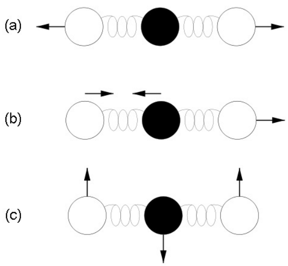

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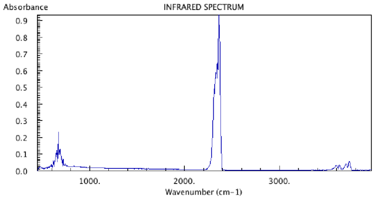
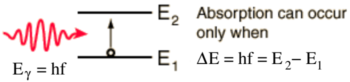
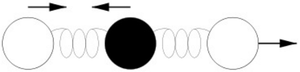


The peak is located at the frequency of light that is absorbed as the CO_2 molecule goes from one quantized energy state to a higher one. The energy of the light is $E_\gamma = hf$ where h is Planck's constant.



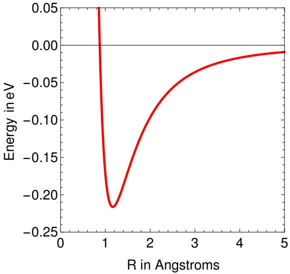
The atoms vibrate in the asymmetric mode shown here. This mode gives CO_2 some of its greenhouse gas properties.

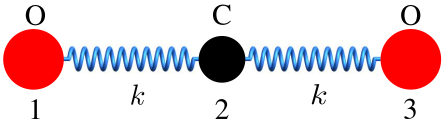
(b)



To do the quantum mechanics we solve the Schroedinger equation built on the classical physics of CO_2.

Our picture of atomic motion in a molecule is built around classical ideas. Consider the CO_2 molecule below. The interactions of the atoms is described as point particles attached by springs. The spring constant for the $C-O$ bond is $139.0\ \mathrm{eV}/\text{Å}^2$ derived from the $C-O$ bond potential shown below. Suppose our 'toy' CO_2 molecule is 'plucked' by pulling the left-hand-side oxygen atom 0.2 Å to the left and the right-hand-side oxygen 0.2 Å to the right. Both atoms are then released from rest. What is the position of each atom in the molecule as a function of time?





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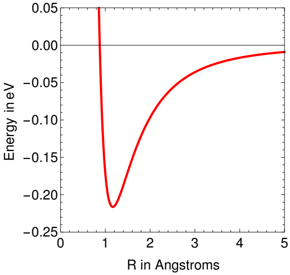
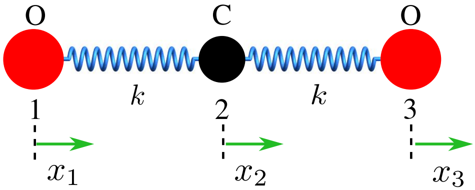
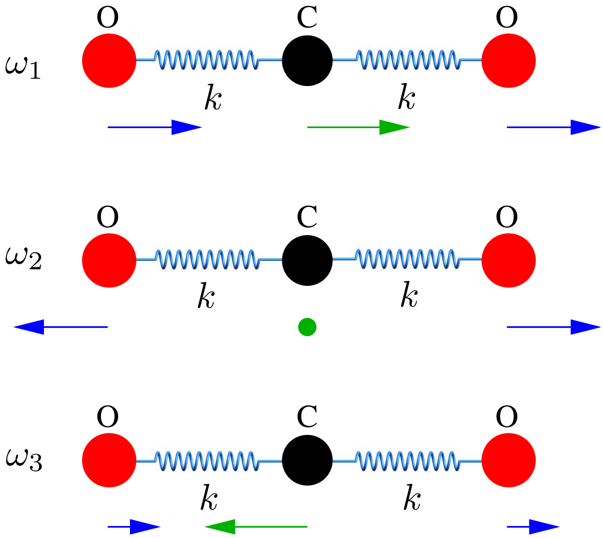
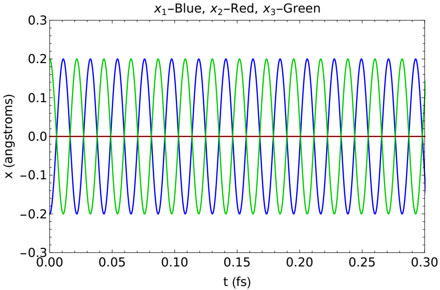






Green vectors - carbon

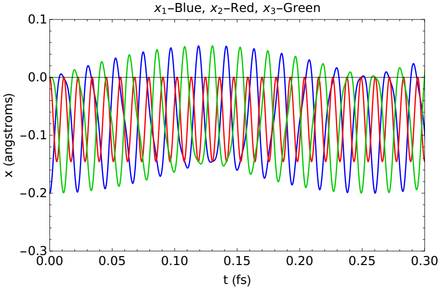
Blue vectors - oxygen



Symmetric mode

$x_1 = d,\ x_2 = 0,\ x_3 = -d$

$\dot{x}_1 = \dot{x}_2 = \dot{x}_3 = 0$



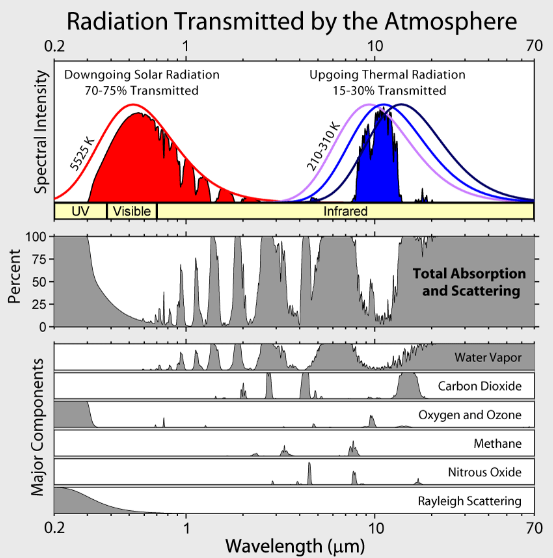
Anti-symmetric mode

$x_1 = d,\ x_2 = -d,\ x_3 = 0$

$\dot{x}_1 = \dot{x}_2 = \dot{x}_3 = 0$

The figure to the right shows absorption bands in the atmosphere (middle panel) and the effect on both solar radiation and upgoing thermal radiation (top panel). Absorption spectrum for major greenhouse gases plus Rayleigh scattering are shown in the lower panel.

The properties of absorption bands are determined by the chemical properties of the gases present. Water vapor is the most significant, followed by carbon dioxide and various others. These processes capture and redistribute 25-30% of the energy in sunlight while the greenhouse gases capture 70-85% of the energy in upgoing thermal radiation.



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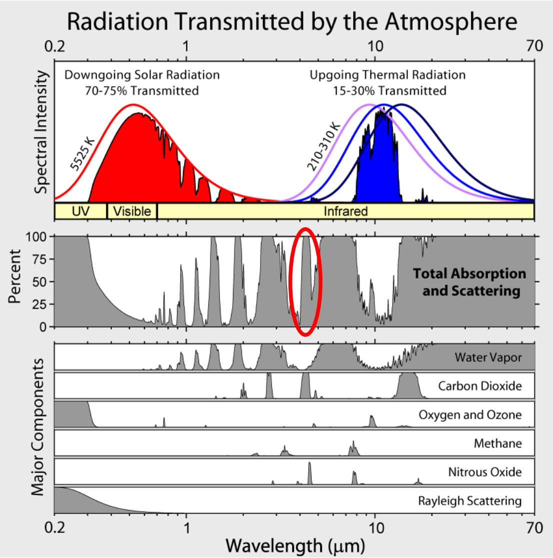
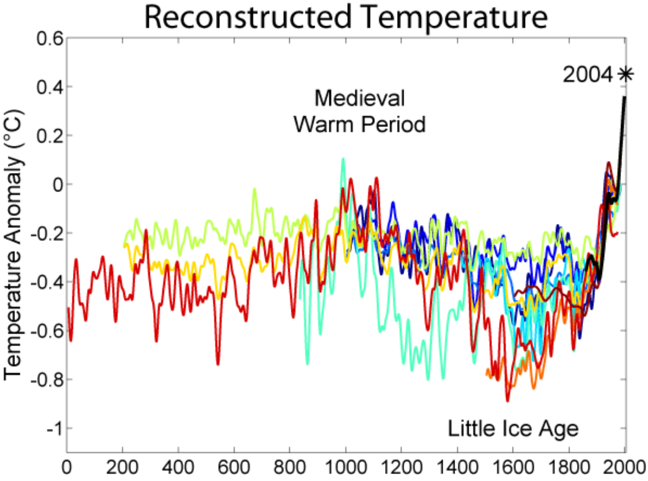


The surface temperature anomaly for the last two thousand years is shown below for measurements up to the year 2004.



R. A. Rohde - `http://www.globalwarmingart.com/wiki/File:1000_Year_Temperature_Comparison.png`

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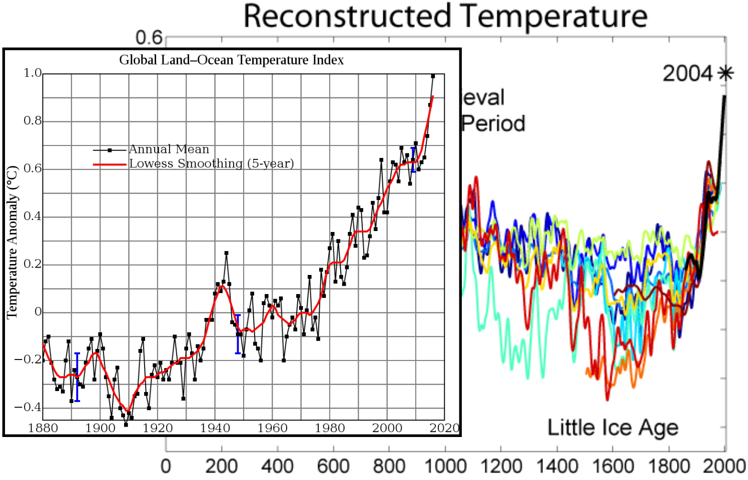

R. A. Rohde - `http://www.globalwarmingart.com/wiki/File:1000_Year_Temperature_Comparison.png`

The second scientific reality, arising from peculiarities of the carbon dioxide molecule, is that the warming influence of the gas in the atmosphere changes less than proportionately as the concentration changes. The practical implication of this slow logarithmic dependence is that eliminating a ton of emissions in the middle of the 21st century will exert only half of the cooling influence that it would have had in the middle of the 20th century.

- Steve Koonin
(NYT, 11/4/15)