Essential Physics I

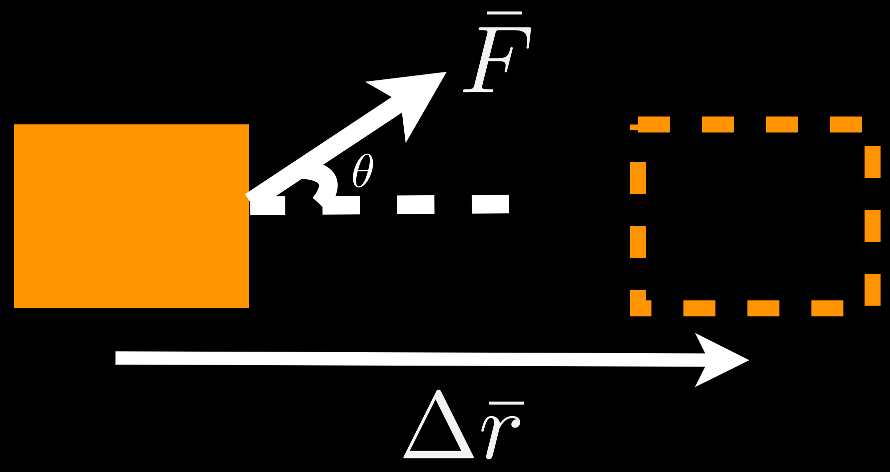
英語で物理学の

エッセンス I

Lecture 7:   30-05-16

Last lecture: review

Work:



$$W = \bar{F}\cdot\Delta\bar{r}$$
$$= F\Delta r\cos\theta$$
$$= F_x\Delta r_x + F_y\Delta r_y + F_z\Delta r_z$$
$$= \int_{x_1}^{x_2} F(x)dx$$

Kinetic energy:

$$K = \frac{1}{2}mv^2$$

$$\Delta K = W_{\mathrm{net}}$$ (Work-energy theorem)

Power:

$$P = \frac{dW}{dt} = \bar{F}\cdot\bar{v}$$

Last lecture: review

Quiz

3 forces: $F_1 = x^{1/2}$

$F_2 = x$

$F_3 = x^2$ (x position in m)

act on an object from x = 0 to x = 1 m.

Each force has the same value at x = 0 and x = 1, but which does the most work?

(a) $F_1 = x^{1/2}$

(b) $F_2 = x$

(c) $F_3 = x^2$

Last lecture: review

Quiz

3 forces:

$$F_1 = x^{1/2}$$

$$F_2 = x$$

$$F_3 = x^2$$

(x position in m)

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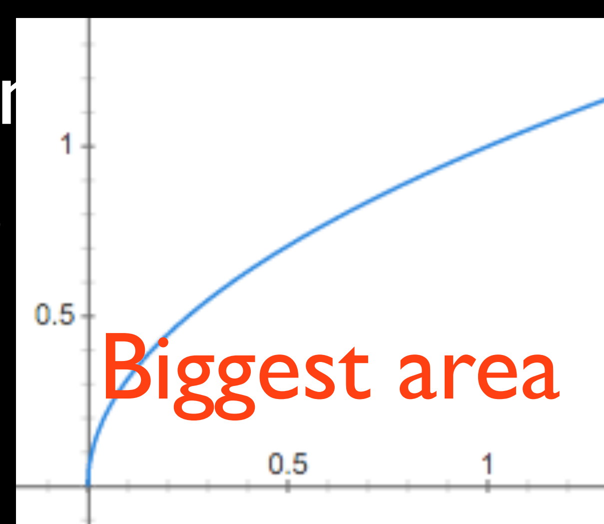
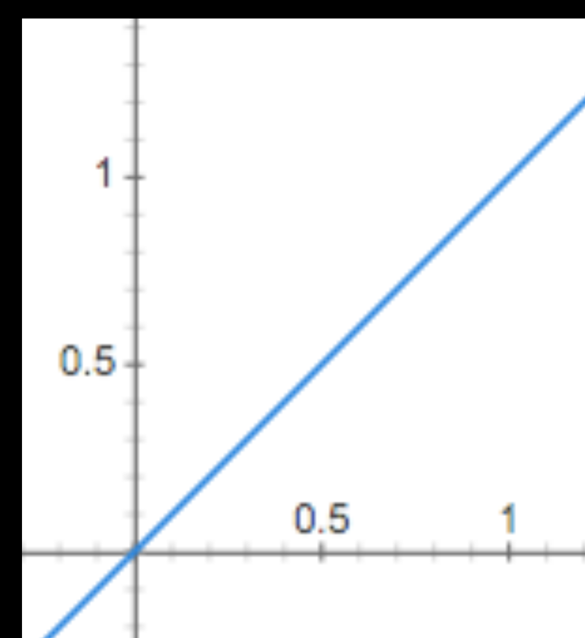
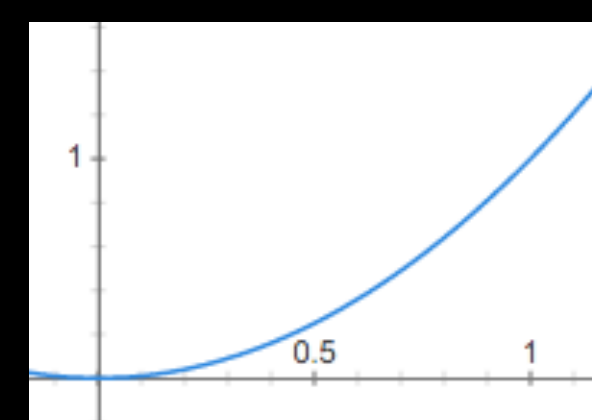






(a) $F_1 = x^{1/2}$

(b) $F_2 = x$

(c) $F_3 = x^2$

Last lecture: review

Quiz

3 objects (A, B and C) are moved $\Delta\bar{r}$

Object A is pushed in the direction of motion with a force, F

Object B is pushed at a 45° angle in the direction of motion with a force, 2F

Object C is pushed at a 90° angle in the direction of motion with a force, 2F

Rank work done, smallest $\rightarrow$ largest

(a) $W_C > W_B > W_A$

(c) $W_B > W_A > W_C$

(b) $W_B > W_C > W_A$

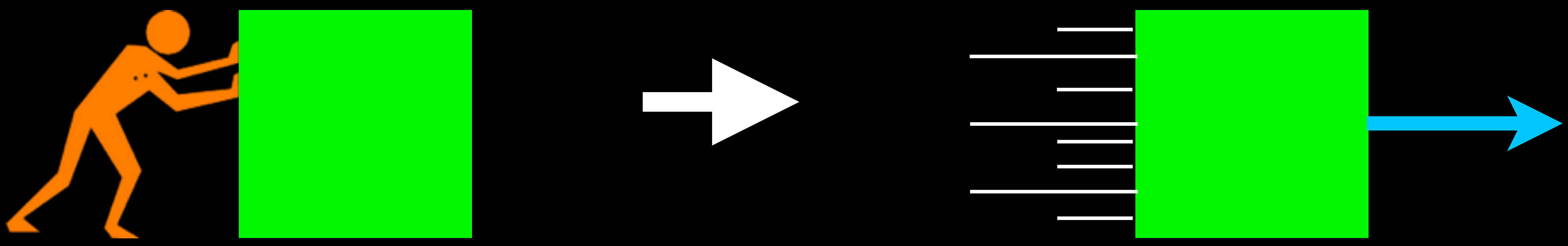
(d) $W_A > W_B > W_C$

Lecture 7

What happens when you drop a book?

Last lecture

Work: $W = \bar{F} \cdot \Delta \bar{r}$



Work-energy theorem: $\Delta K = W_{\rm net}$

Work done is converted into kinetic energy ..... right?

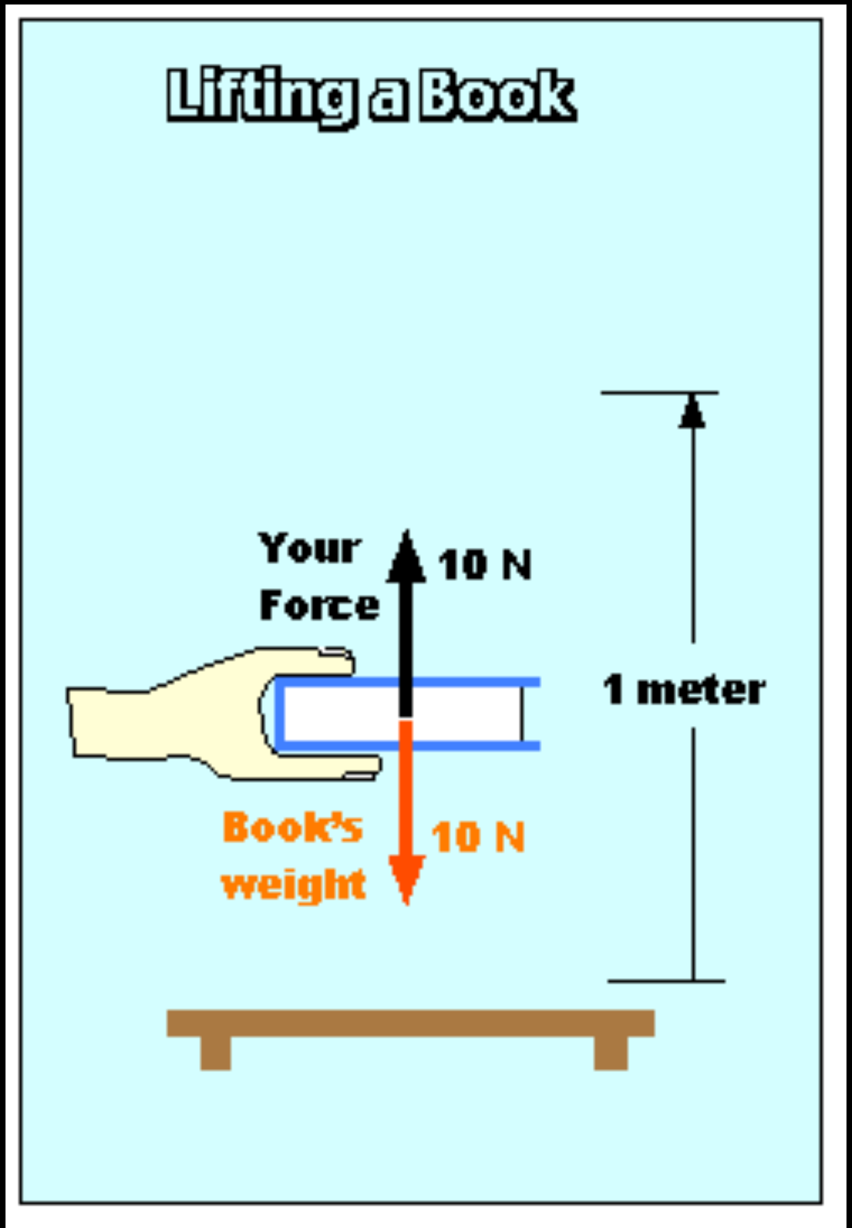
Energy

What about if you lift a book?

Book's weight: $F_g = mg = 10\text{N}$

Displacement: $\Delta r = \Delta y = 1\text{m}$

Work done by my force: $W = (10\text{N}) \times (1\text{m}) = 10J$



What about kinetic energy?

$$K = \frac{1}{2}mv^2 = ?$$

The book's velocity does not increase,

so K does not increase: $\Delta K = 0$

Where did the energy go?

Energy

Wait! There is a 2nd force.

Gravity exerts a downwards force on the book:

Work done by my force:

$$W_{\rm me} = \bar{F} \cdot \Delta\bar{r}$$

Work done by gravity's force:

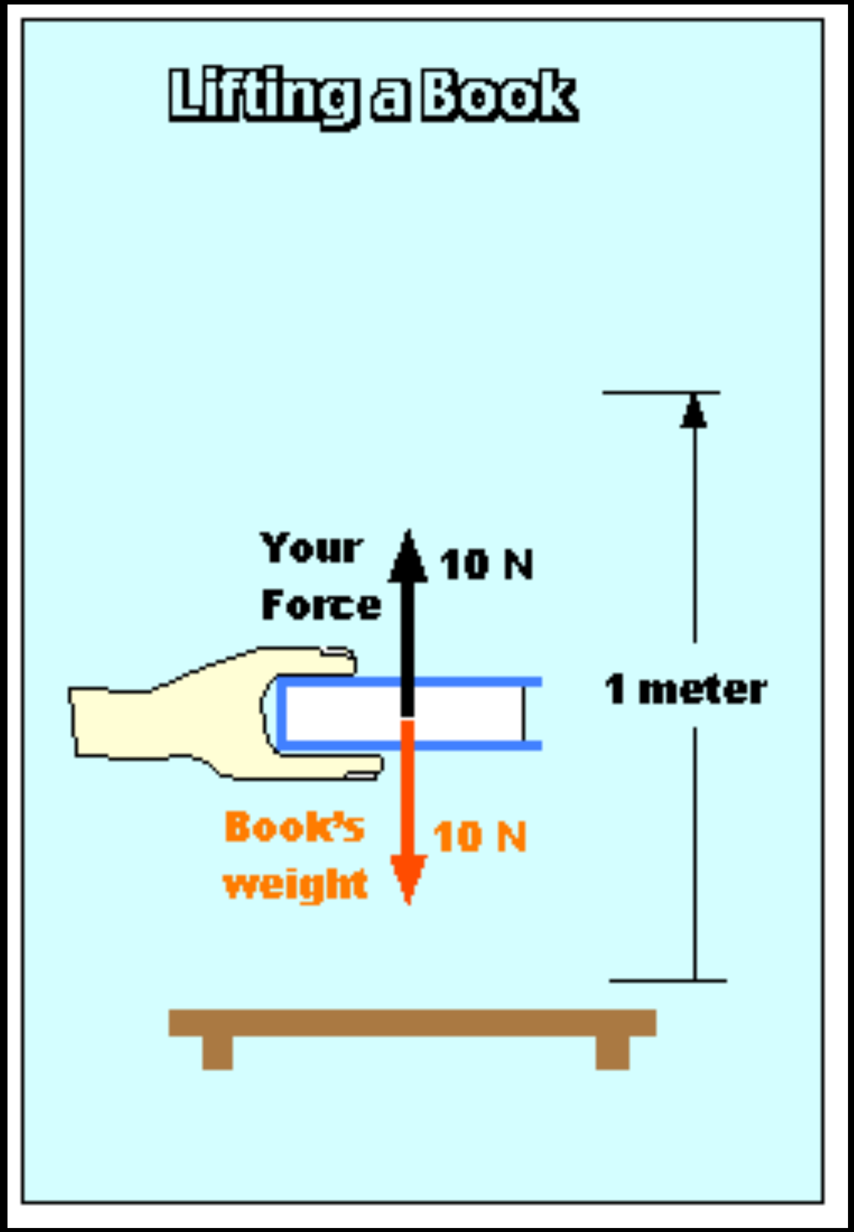
$$W_{\rm grav} = -\bar{F} \cdot \Delta\bar{r}$$

Net work:

$$W_{\rm net} = W_{\rm me} + W_{\rm grav} = 0J$$

Therefore:

$$\Delta K = W_{\rm net} = 0$$



Energy

We gave the book 10 J of energy

10J

$$W_{\text{me}} = \bar{F} \cdot \Delta \bar{r}$$

$$\Delta K = W_{\text{net}} = 0$$

Gravity took 10 J of energy from the book

10J

$$W_{\text{grav}} = -\bar{F} \cdot \Delta \bar{r}$$

?

Where did gravity's energy go?

Energy

What happens when you drop the book?

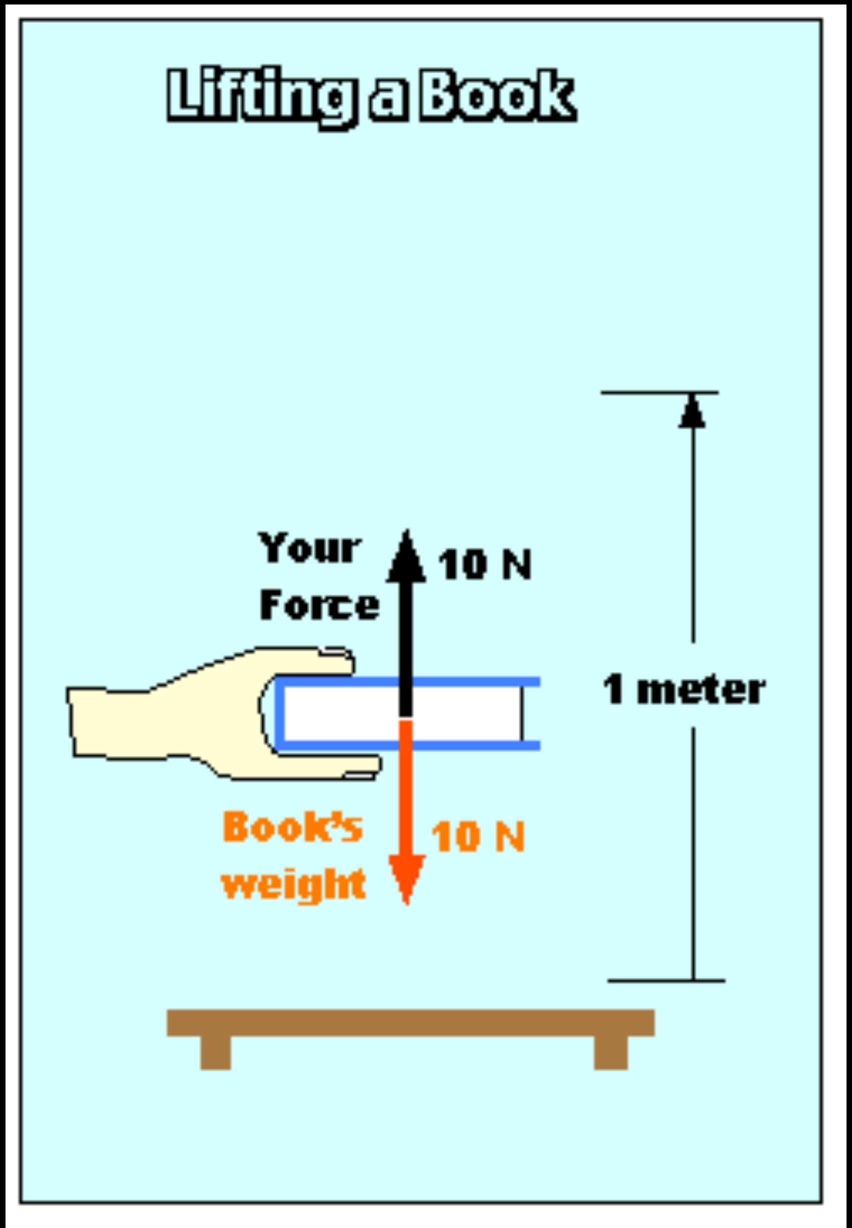
It accelerates down.

Gravity does positive work on the book, returning the 10 J:

$$W_{\text{grav}} = \bar{F} \cdot \Delta \bar{r} = 10\text{J}$$

Which is converted into kinetic energy:

$$K = \frac{1}{2} m v^2 = 10\text{J}$$

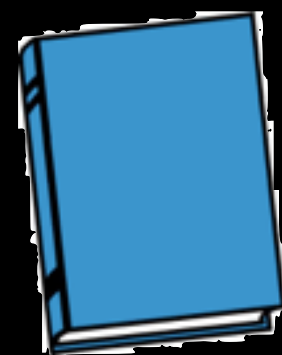


Energy

We gave the book 10 J of energy

10J

$$W_{\mathrm{me}} = \bar{F} \cdot \Delta \bar{r}$$



$$\Delta K = W_{\mathrm{net}} = 0$$

Gravity took 10 J of energy from the book

10J

$$W_{\mathrm{grav}} = -\bar{F} \cdot \Delta \bar{r}$$

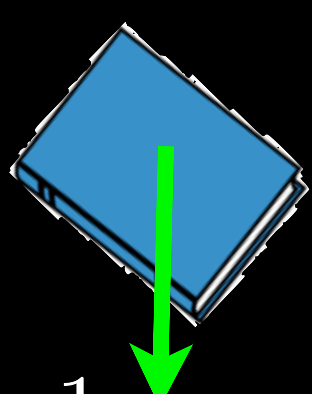
Energy is stored until book is dropped

Gravity gives 10 J of energy to the book

10J

$$W_{\mathrm{grav}} = \bar{F} \cdot \Delta \bar{r}$$

Converted to K as the book falls

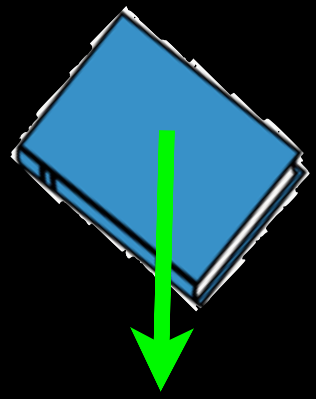


$$K = \frac{1}{2}mv^2 = 10\mathrm{J}$$

Potential Energy

"Stored energy" is called potential energy

It is 'stored', because we can get it back as kinetic energy



$$\Delta U \rightarrow K$$

Forces that store the energy they use are called conservative forces

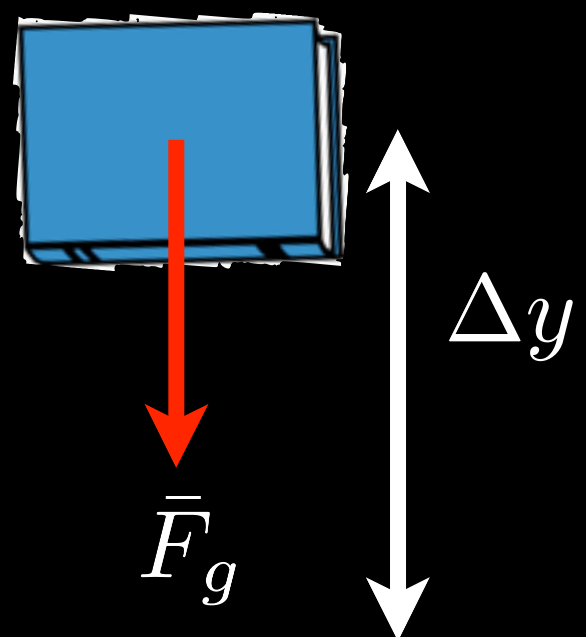
e.g. gravity springs

negative work done by a conservative force:

$$W_{\text{force}} = -\int_A^B \bar{F} \cdot d\bar{r} = \Delta U_{\text{AB}}$$

Conservative Forces

e.g. when lifting a book:



Negative work done by gravity's force: = Potential energy stored

$$W_{\text{grav}} = -\bar{F} \cdot \Delta \bar{r}$$
$$= -mg\Delta y$$

$$\Delta U$$

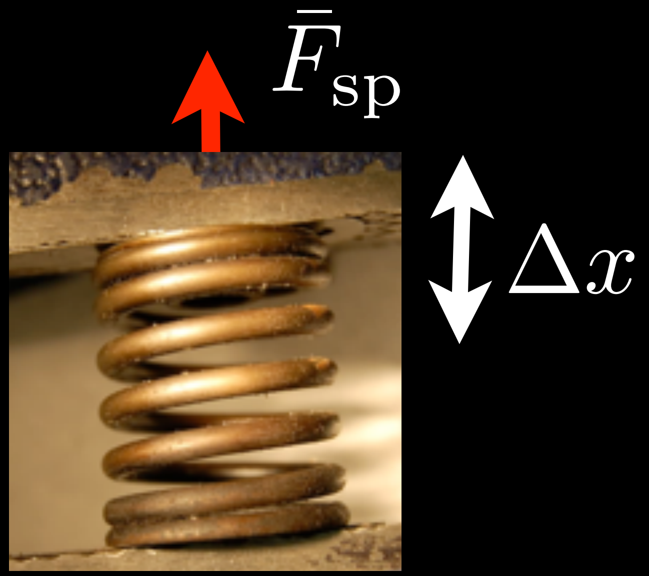
Gravitational potential energy: $$\Delta U = -mg\Delta y$$

The change in potential energy, ΔU is the important quantity.

Therefore, we can chose where $U = 0$

Conservative Forces

e.g. when compressing a spring:



Negative work done by the spring's force: = Potential energy stored

$$W_{\text{sp}} = -\int_{x_1}^{x_2} \bar{F} \cdot d\bar{r}$$

$$\Delta U$$

$$= -\int_{x_1}^{x_2} (-kx)dx$$

$$= \frac{1}{2}kx_2^2 - \frac{1}{2}kx_1^2$$

Elastic potential energy:

$$U = \frac{1}{2}kx^2$$

(If we chose $U = 0$ to be when $x = 0$)

Conservative Forces

Quiz

You lift a 10 kg bag from the floor to a shelf 2m above the floor.

Which of the following is true?

(A) You increased the gravitational potential energy and performed negative work on the bag.

(B) You increased the gravitational potential energy and the earth performed positive work on the bag.

(C) You increased the gravitational potential energy and the earth performed negative work on the bag.

(D) You decreased the gravitational potential energy and the earth performed positive work on the bag.

Conservative Forces

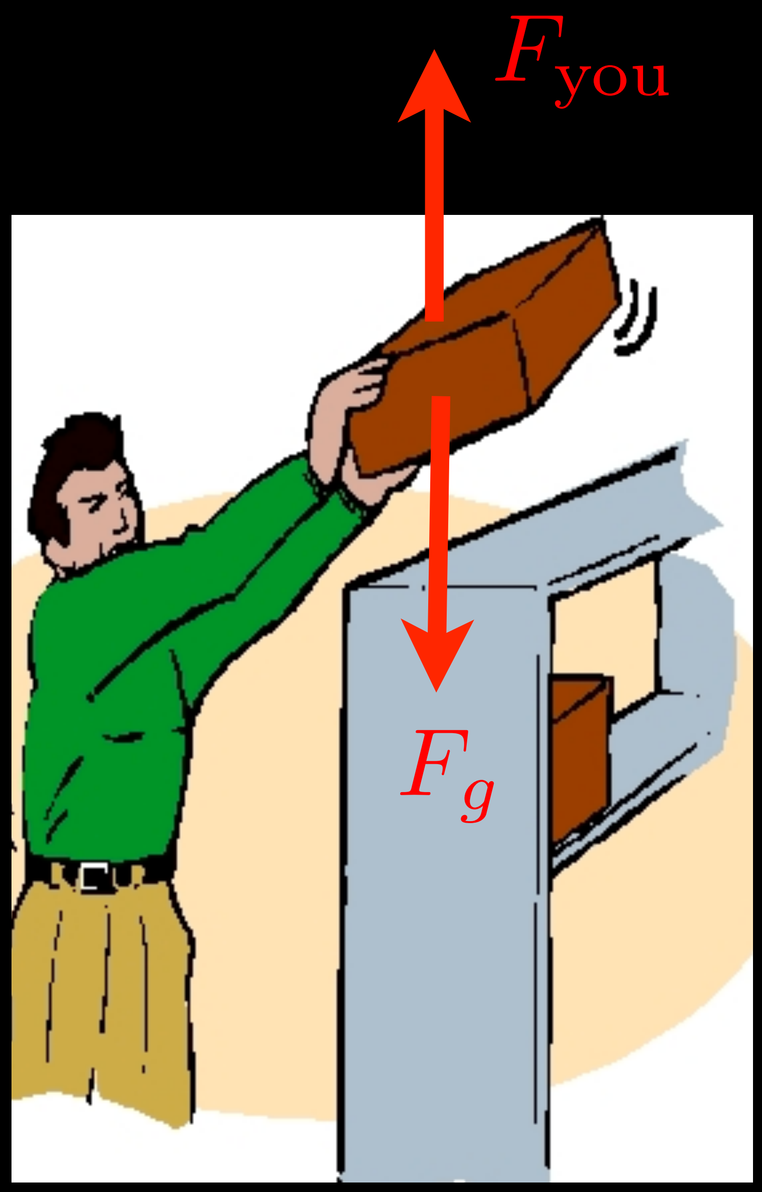
Quiz

(C) You increased the gravitational potential energy and the earth performed negative work on the bag.

You did positive work on the bag.

Gravity did negative work on the bag.

The gravitational potential energy (U) of the bag increased.



Conservative Forces

Quiz

A woman runs up a flight of stairs.

The gain in her gravitational potential energy is U.

If she runs up the same stairs with twice the speed, what is her gain in potential?

(A) U

(B) 2U

(C) U/2

(D) 4U

(E) U/4

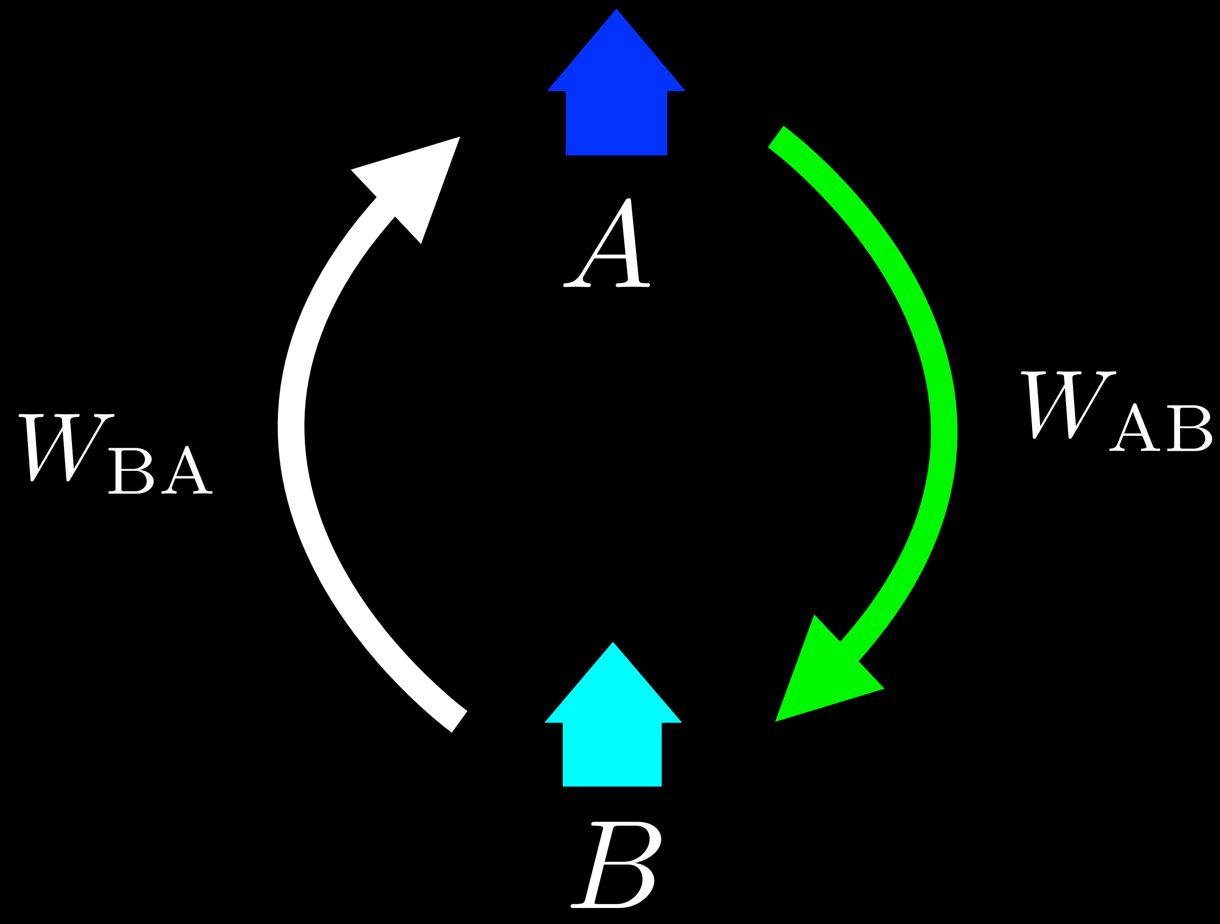
Conservative Forces

How do we know if a force is conservative?

If the total work done in moving from $A \rightarrow B \rightarrow A \;= 0\,,$

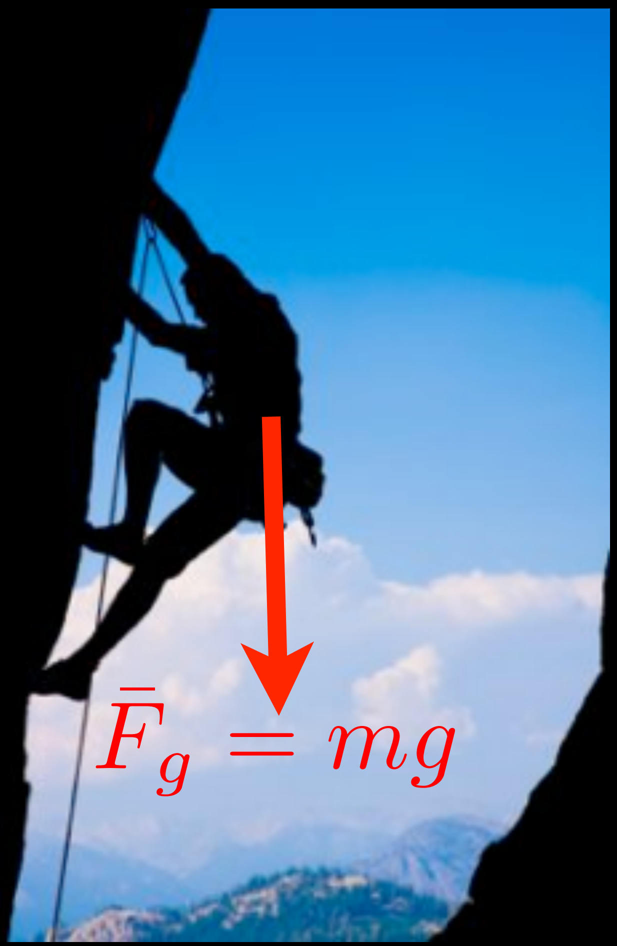
then the force is conservative.

$$W_{\mathrm{AB}} + W_{\mathrm{BA}} = 0$$



Conservative Forces

e.g. climbing a mountain



Climbing up

Work done by gravity: $W_{\mathrm{grav,up}} = -mg\Delta y$

Climbing down

Work done by gravity: $W_{\mathrm{grav,down}} = mg\Delta y$

$W_{\mathrm{net}} = -mg\Delta y + mg\Delta y = 0$

Gravity is conservative

Conservative Forces

e.g. pushing a box

Pushed across room from $A \to B$

Work done by friction:

$$W_{\rm fric, A\to B} = -F_{\rm fric}\Delta x$$

$$= -\mu_k N \Delta x \;\; = -\mu_k mg\Delta x$$

Pushed back from $B \to A$

Friction always opposes motion

$$W_{\rm fric, B\to A} = -\mu_k mg\Delta x$$

$$W_{\rm net} = -2\mu_k mg\Delta x \neq 0$$

Friction is not conservative

Conservative Forces

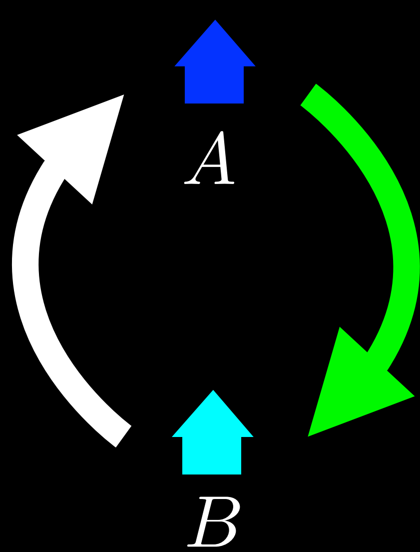
Mathematically:

$$\oint \bar{F} \cdot d\bar{r} = 0$$ conservative force

work

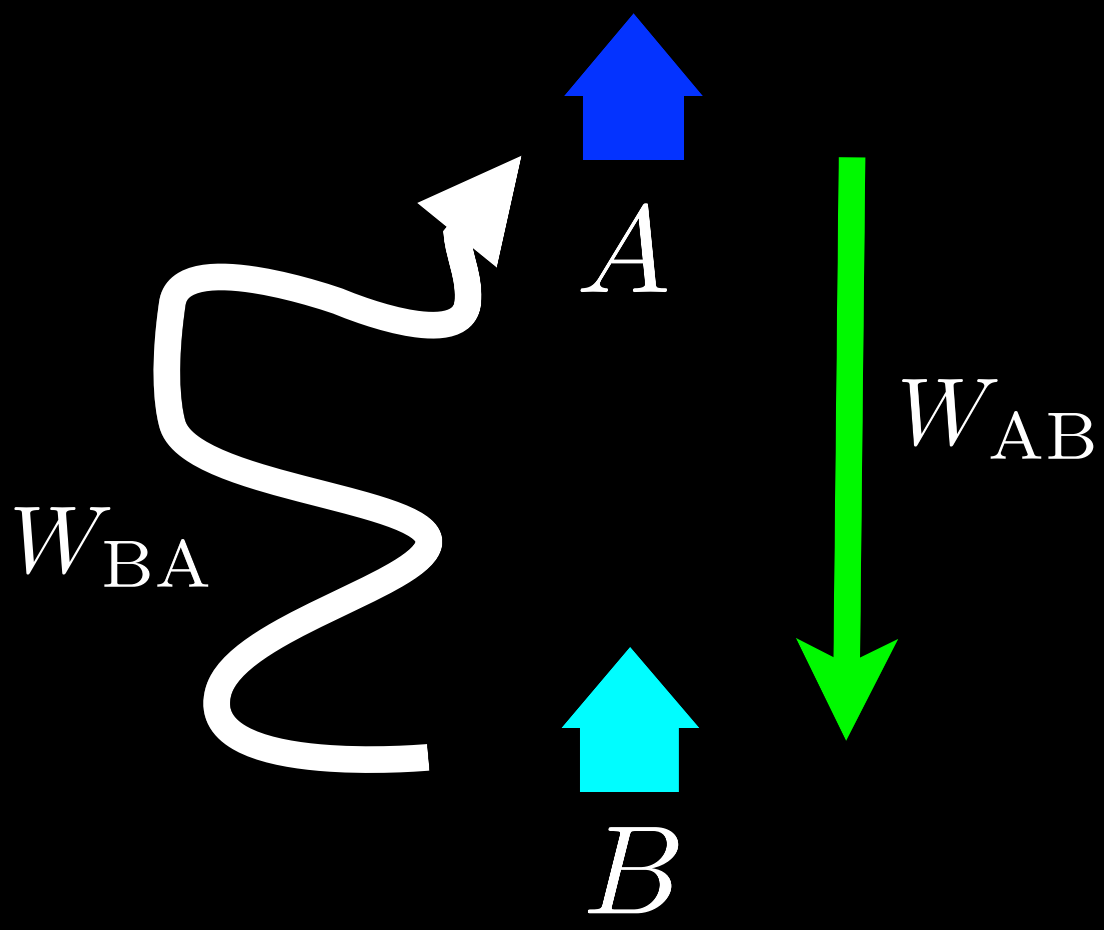
closed path integral

$$\int_{x_1}^{x_2} \xrightarrow{x_1 = x_2} \oint$$



Conservative Forces

For a conservative force, the path from $A \rightarrow B$ is not important.



$$\oint \bar{F} \cdot d\bar{r} = W_{AB} + W_{BA} = 0$$

The work done by a conservative force depends only on the end points A and B, not on the path between them.

Conservative Forces

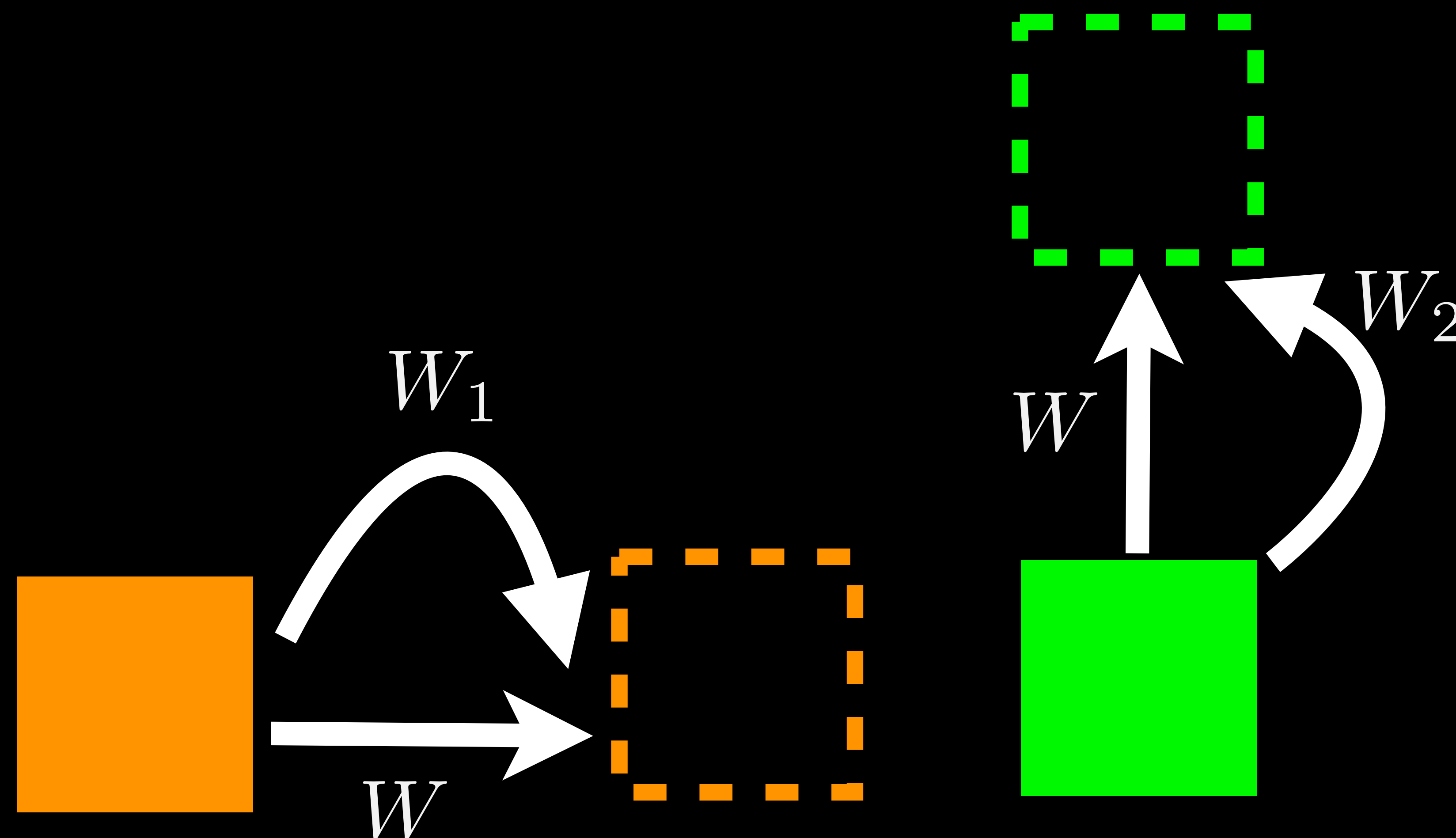
The same amount of work is done pushing a box across a rough floor and lifting a weight the same distance upwards.

How does the work compare if the box and weight are moved on curved paths between the start and end points?

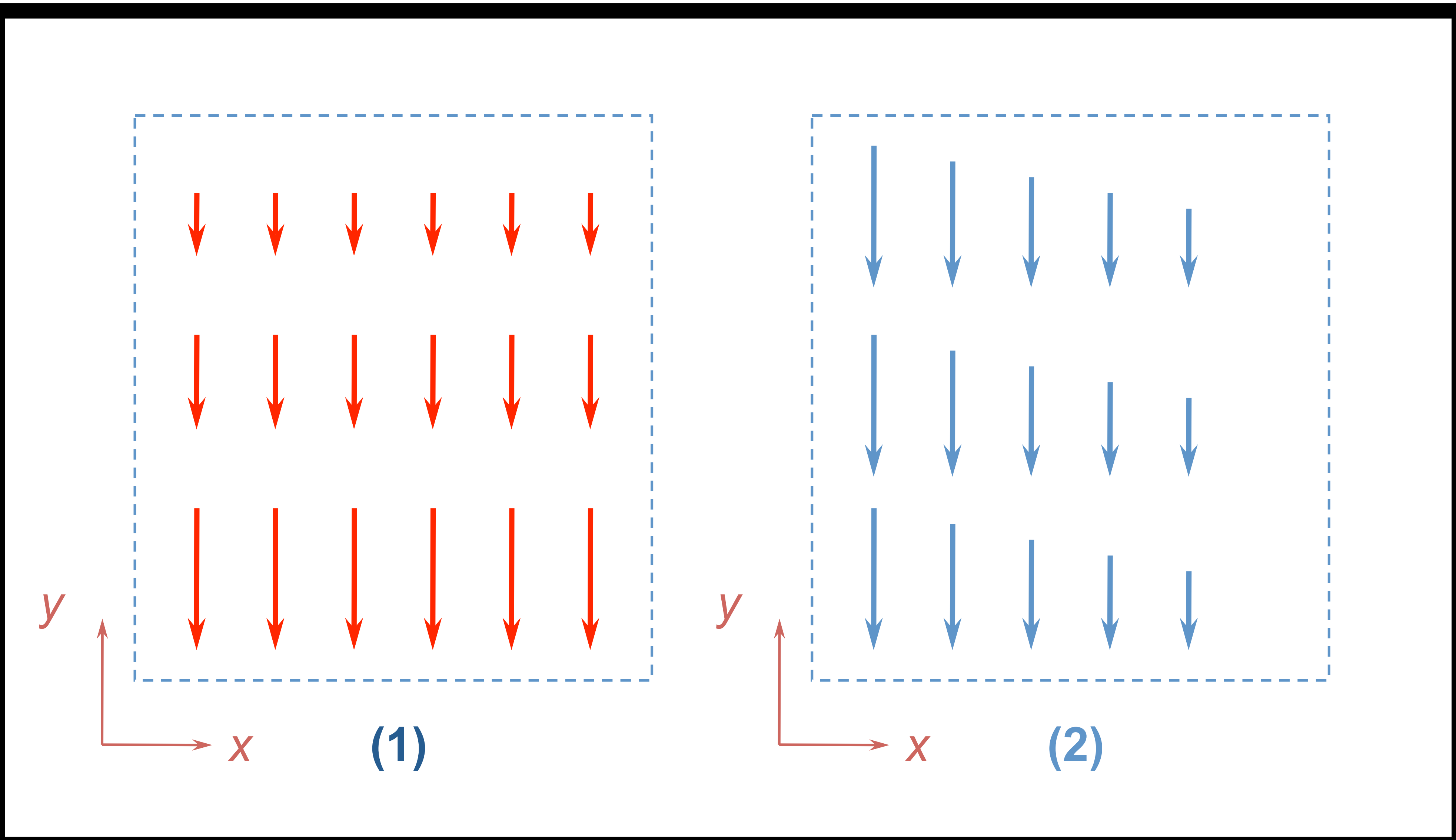
(a) $W = W_1 = W_2$

(b) $W_1 > W$

(c) $W_2 > W$

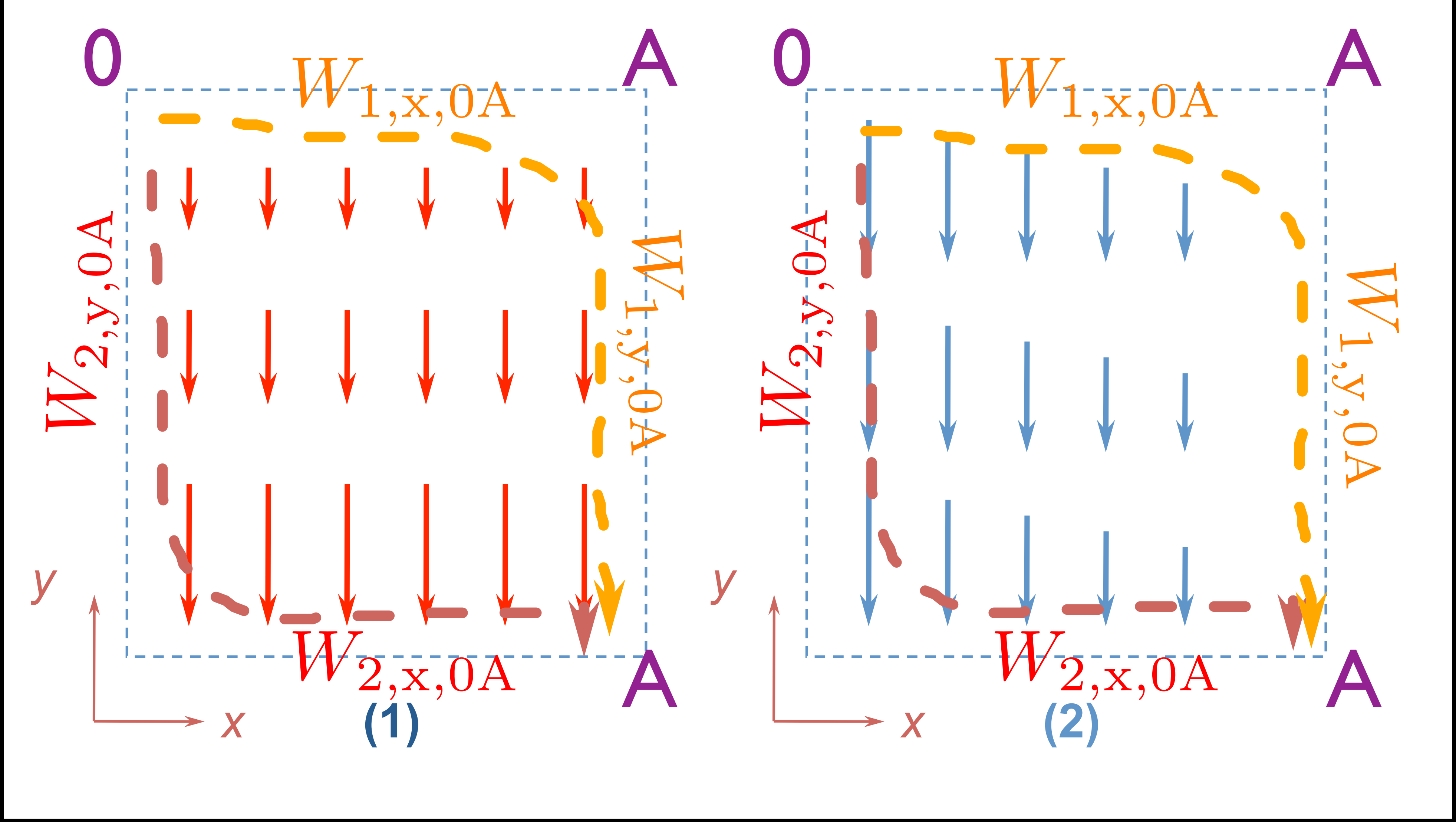


Conservative Forces



Which of these force fields is conservative?

Conservative Forces

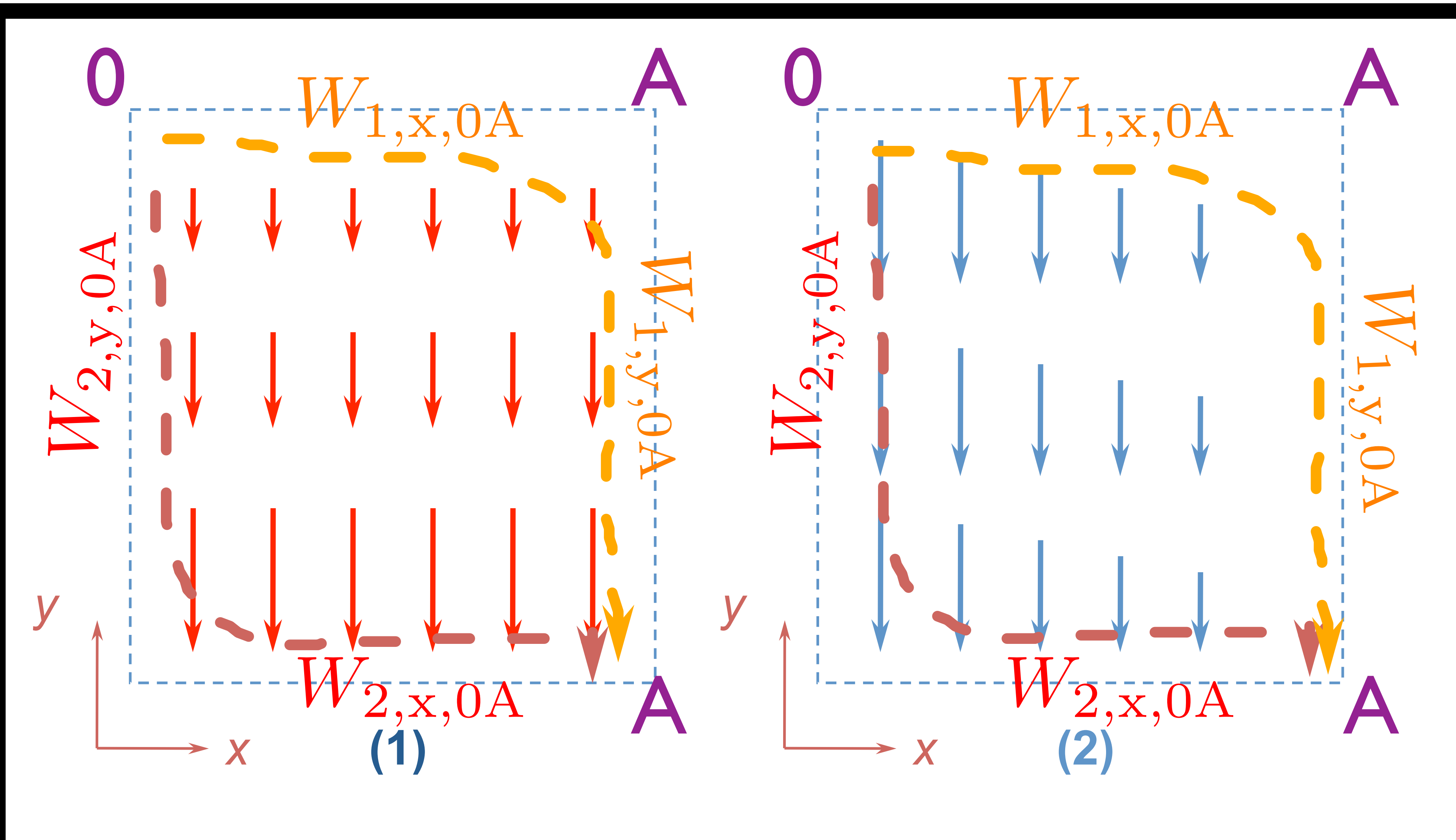


To be conservative: $\oint \bar{F} \cdot d\bar{r} = 0$

$$= W_{1,x,0A} + W_{1,y,0A}$$

$$+ W_{2,x,0A} + W_{2,y,0A}$$

Conservative Forces

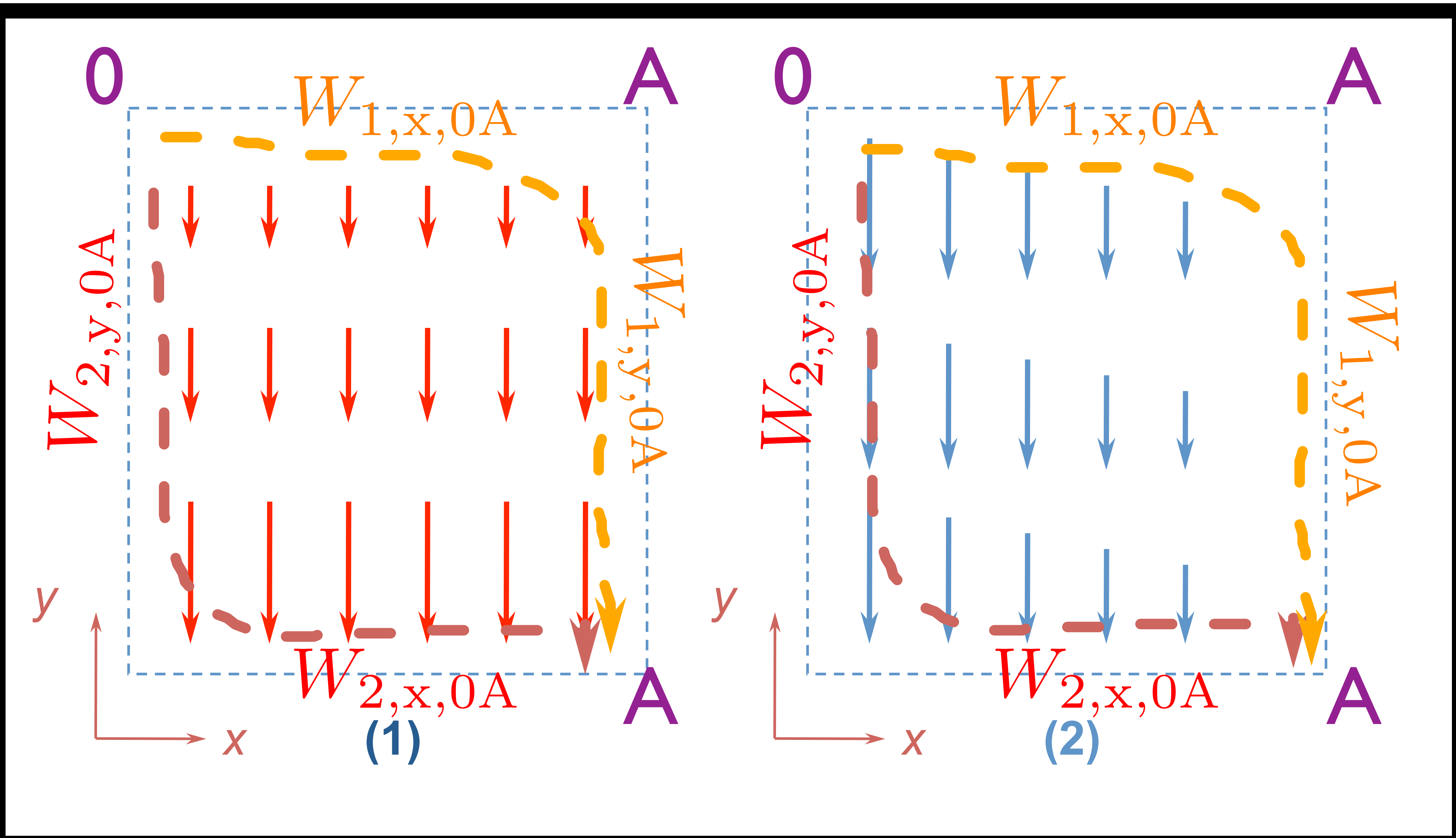


To be conservative: $\oint \bar{F} \cdot d\bar{r} = 0$

$$= \int_0^a \bar{F} \cdot \bar{i} dx + \int_0^a \bar{F} \cdot \bar{j} dx$$

$$+ \int_a^0 \bar{F} \cdot \bar{i} dx + \int_a^0 \bar{F} \cdot \bar{j} dx$$

Conservative Forces



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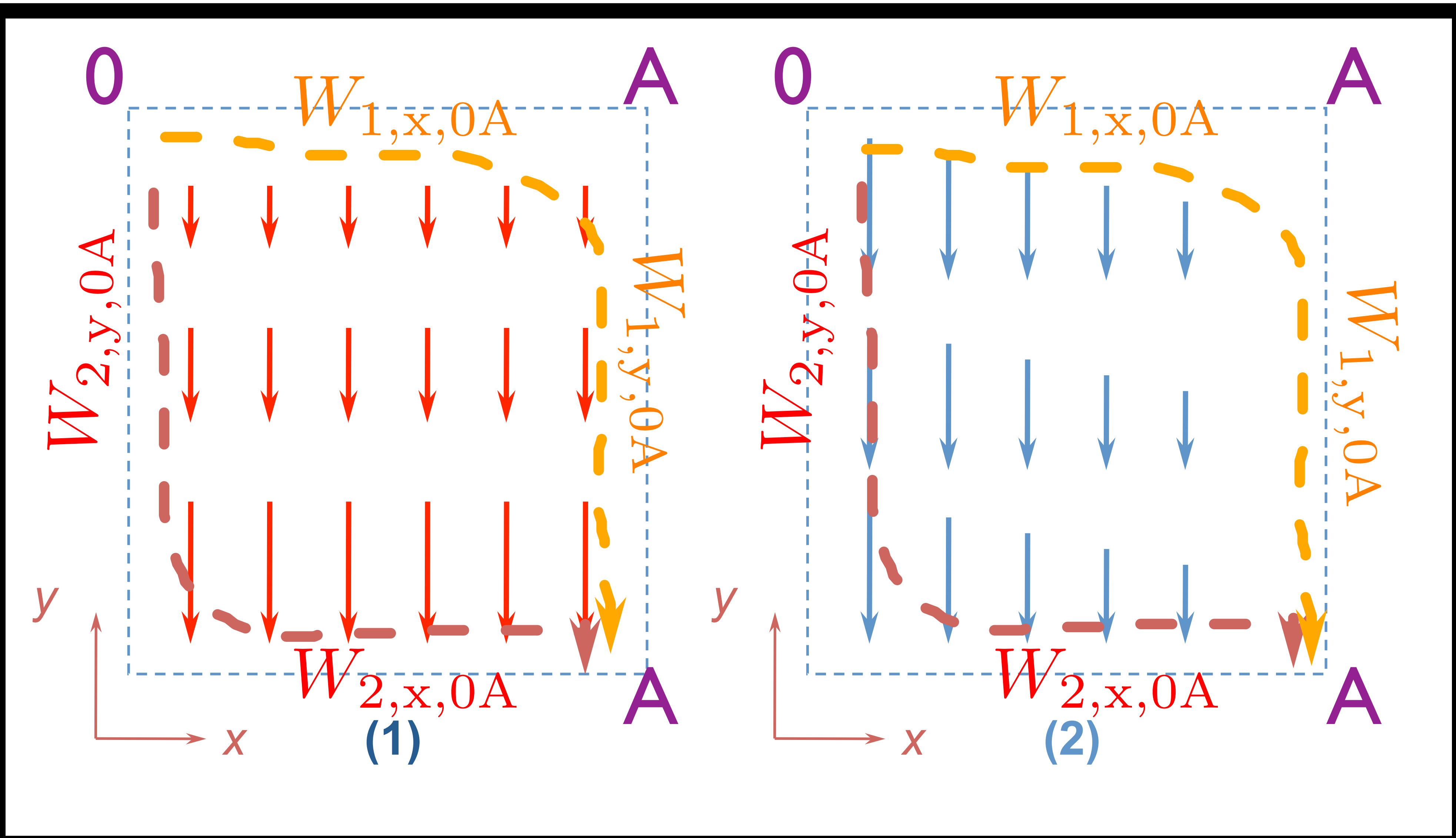
$$+ \int_a^0 \bar{F} \cdot \bar{i} dx + \int_a^0 \bar{F} \cdot \bar{j} dx$$

Force has only j component:

$\bar{F} = F_j$

Conservative Forces



To be conservative: $\oint \bar{F} \cdot d\bar{r} = 0$

$$= \int_0^a \bar{F} \cdot \bar{j} dx + \int_a^0 \bar{F} \cdot \bar{j} dx$$

(1) = 0

Conservative Forces

Quiz

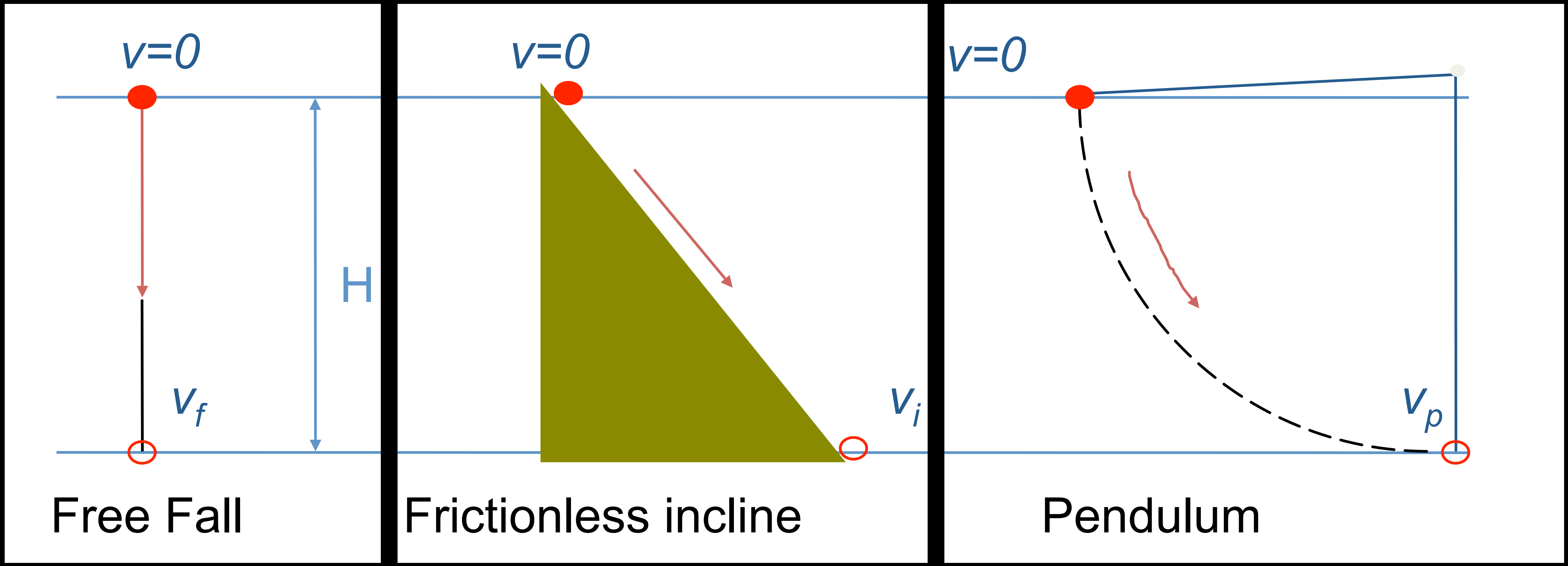
3 objects of mass m begin at height h with velocity 0.0

1 falls straight down

1 slides down a frictionless inclined plane

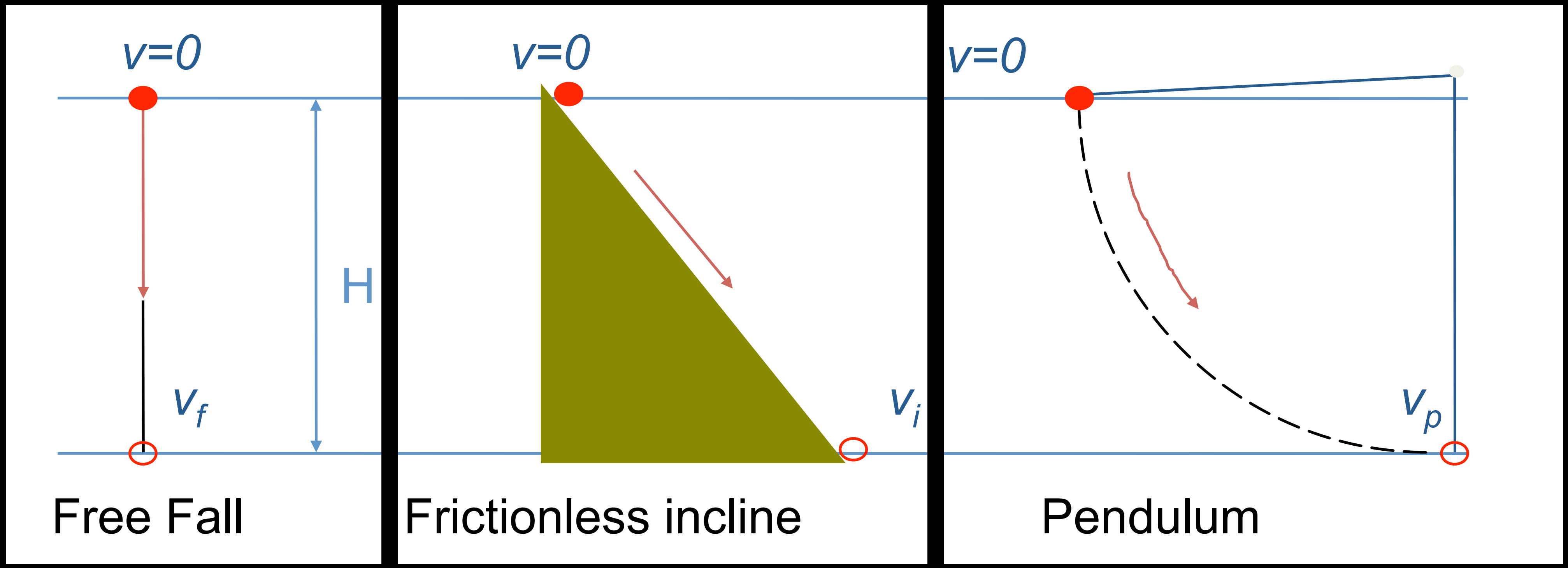
1 swings at the end of a pendulum

What is the relationship between their speeds when they reach height 0?



$(a) V_f > V_i > V_p$ $(b) V_f > V_p > V_i$ $(c) V_f = V_p = V_i$

Conservative Forces



The only work is done by gravity, a conservative force

Therefore, the path doesn't matter

$$U_f = U_p = U_i = mgh \; = K = \frac{1}{2}mv^2$$

$$V_f = V_p = V_i = \sqrt{2gH}$$

Conservative Forces

Quiz

A ball, initially at rest ($v_i = 0$), is dropped from 1.5m.

It is observed to have a velocity v_f just before it hits the floor.

If instead the ball is dropped from 0.5 m what is its velocity?

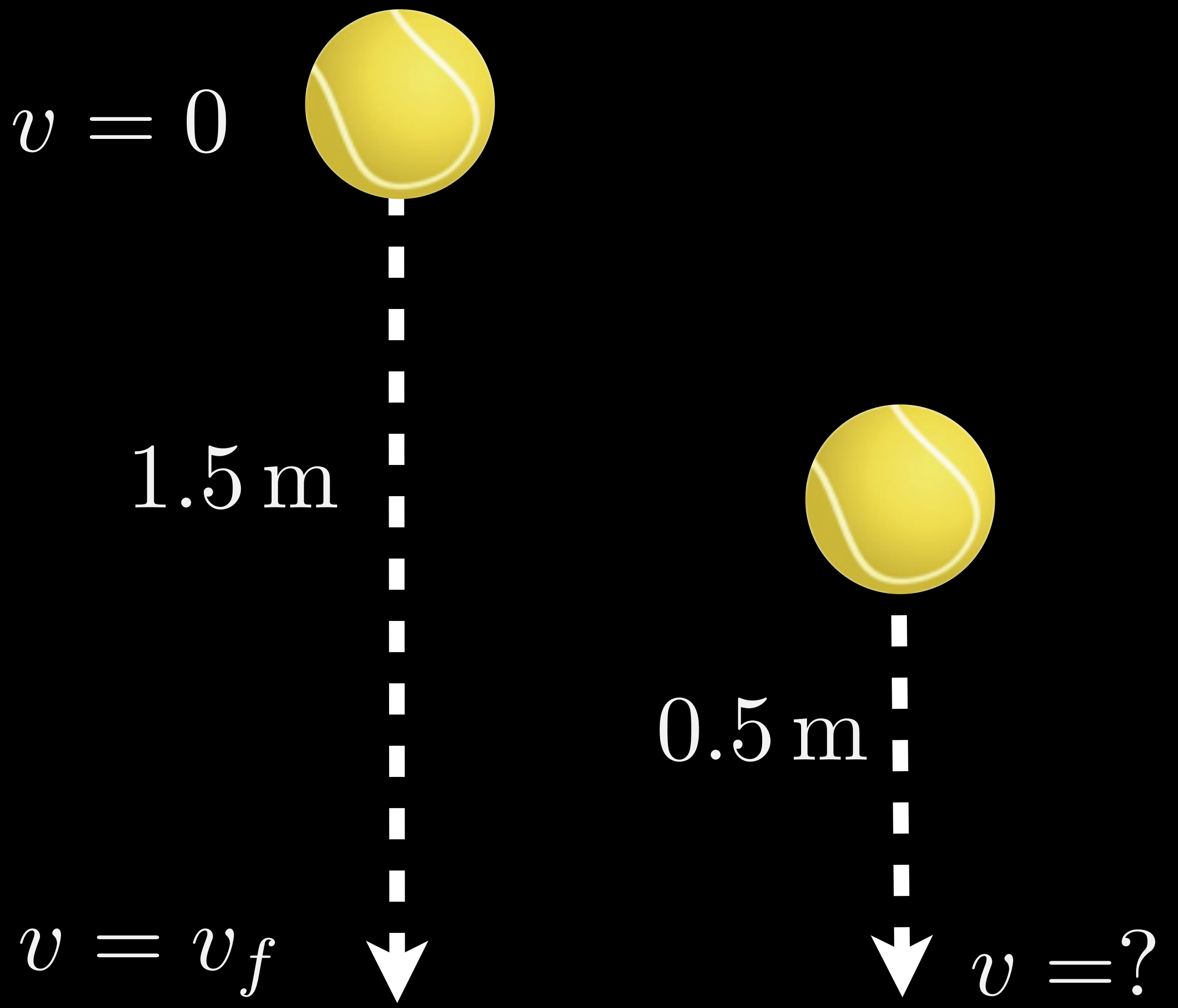
(A) 33% of v_f

(B) 50% of v_f

(C) 58% of v_f

(D) 66% of v_f

(E) 71% of v_f



Conservative Forces

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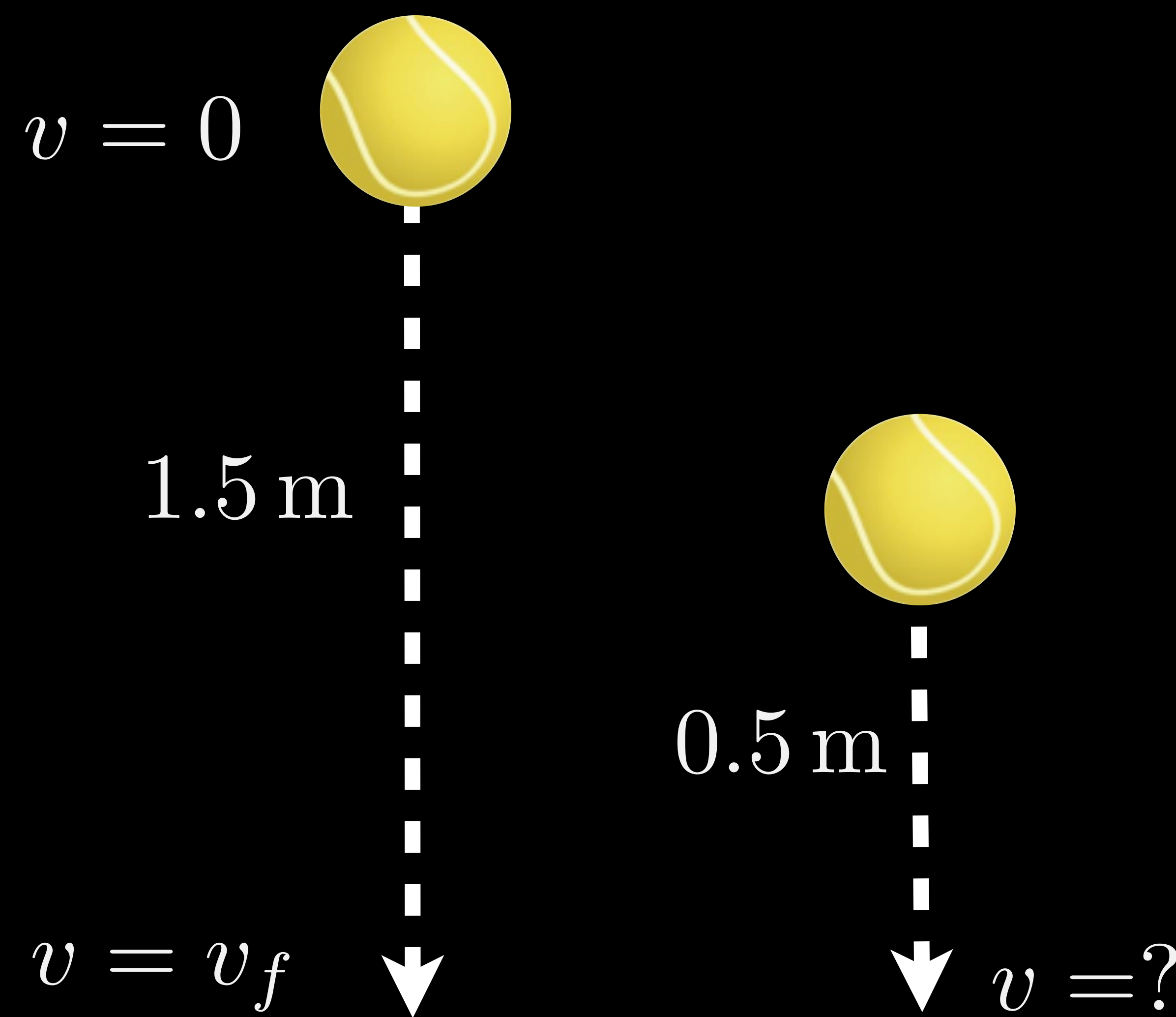
$$U \rightarrow K$$

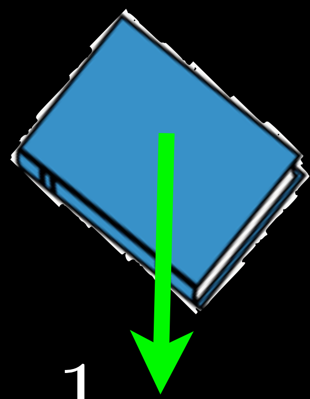
$$mg\Delta y = \frac{1}{2}mv^2$$

$$v = \sqrt{2g\Delta y}$$

$$\frac{v}{v_f} = \sqrt{\frac{0.5}{1.5}} = 57.7\%$$



Energy conservation



$$K = \frac{1}{2}mv^2 = 10\mathrm{J}$$

The book's potential energy (U) becomes kinetic (K)

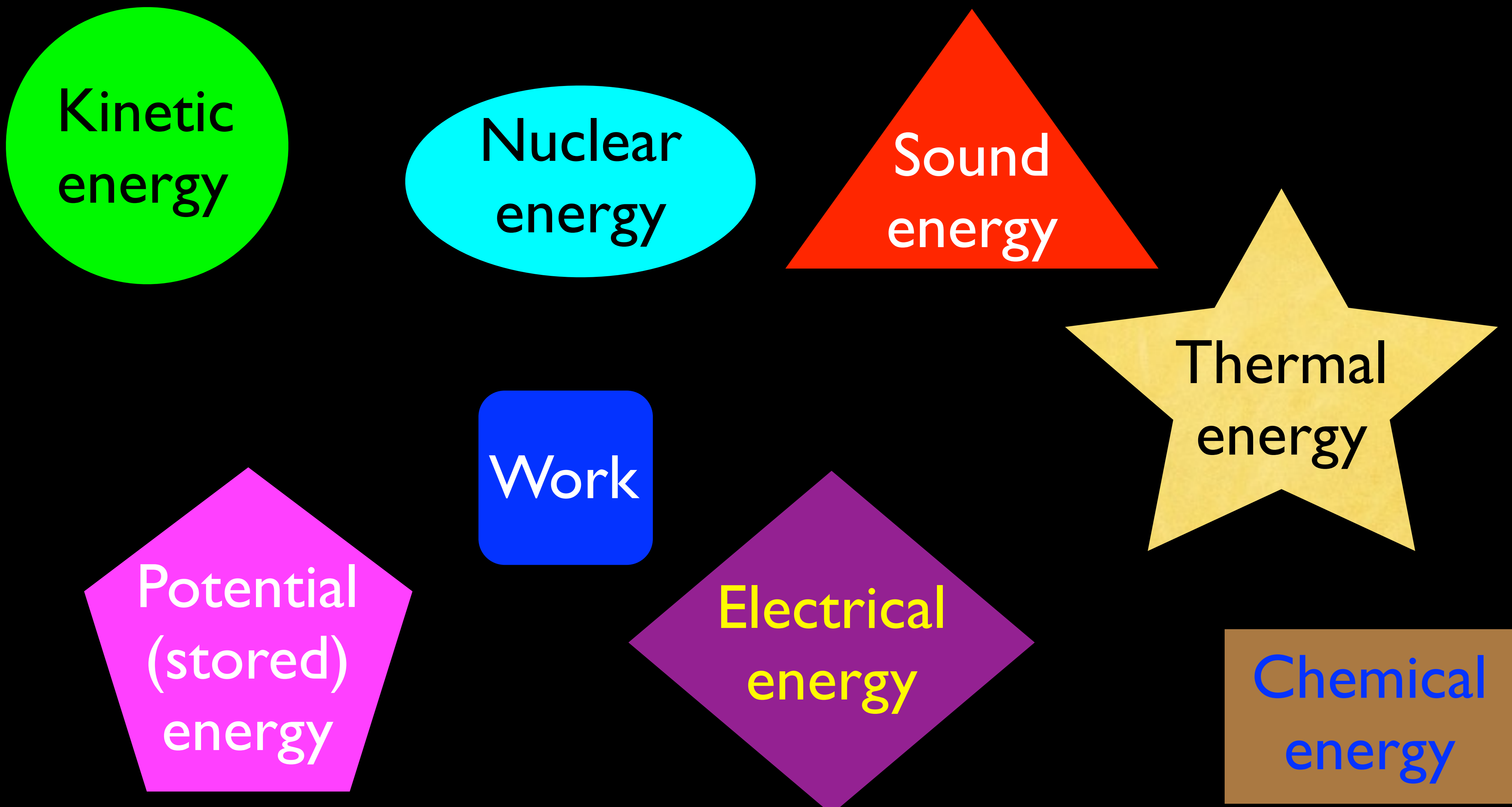
Then what?

Where did the kinetic energy go?

Thermal (heat) energy and sound energy

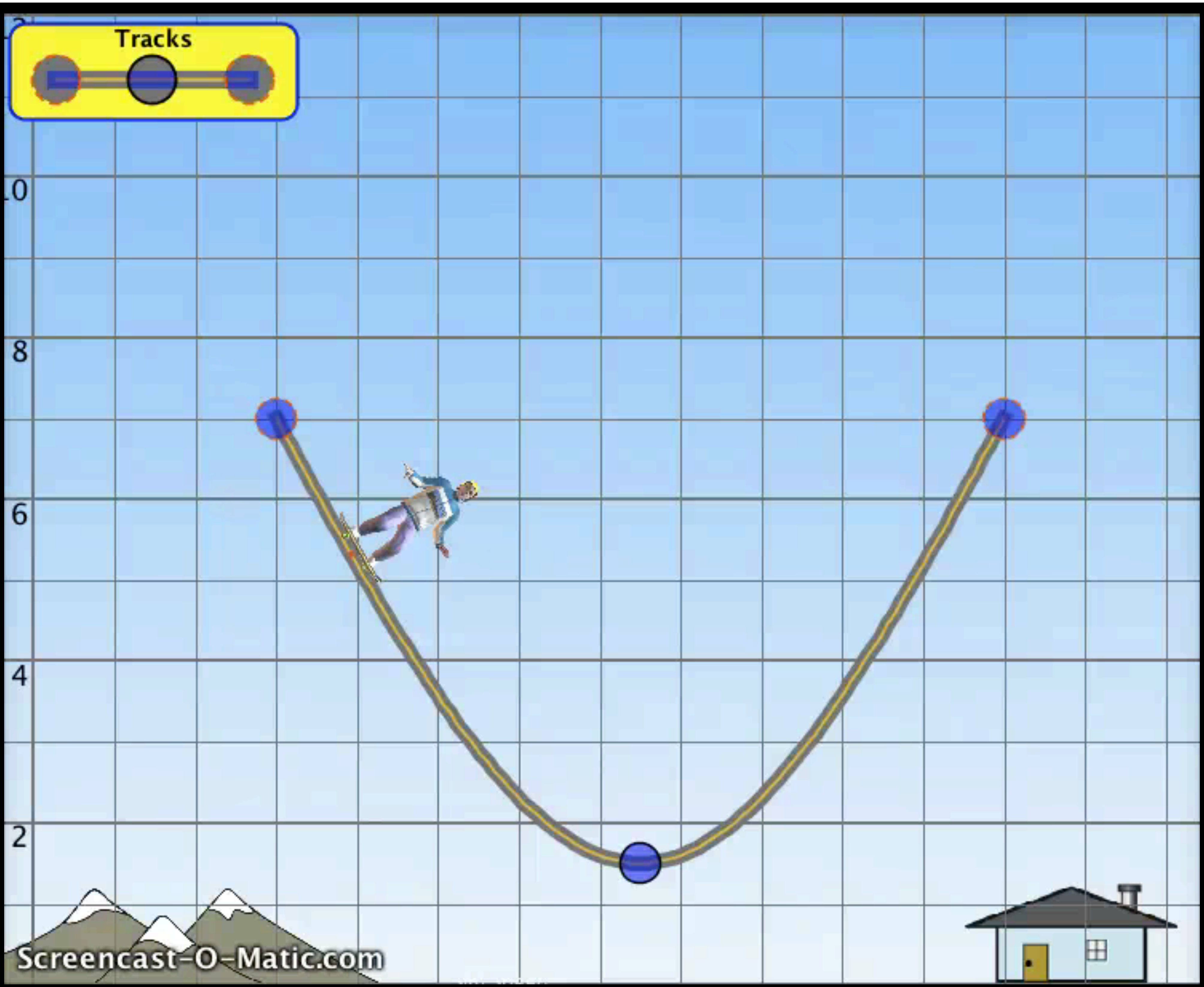
Energy conservation

Energy can be converted between forms:

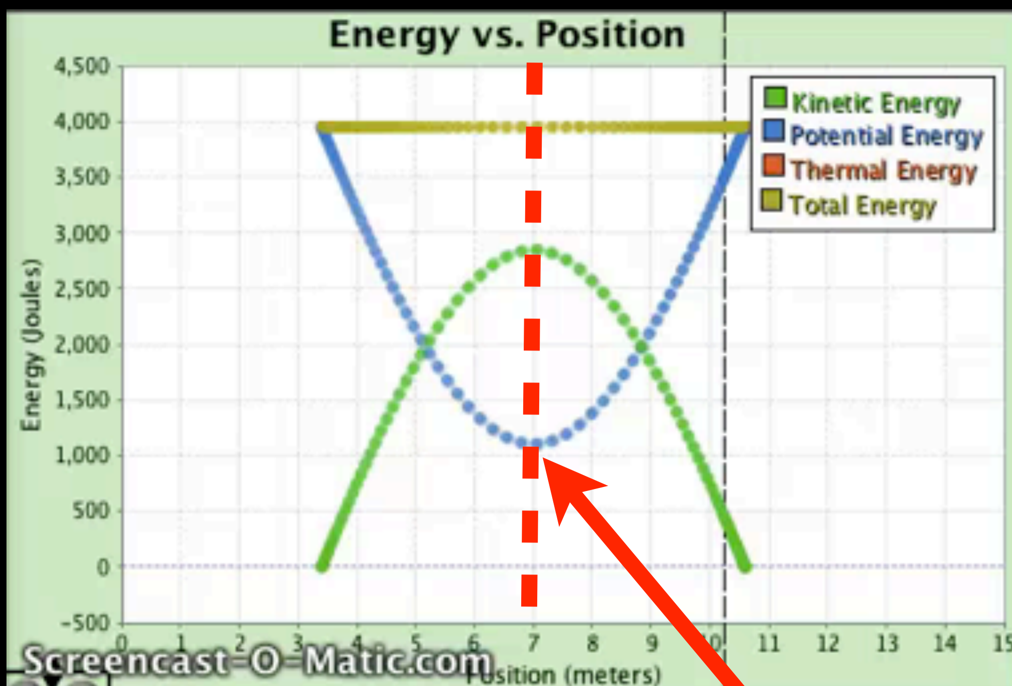


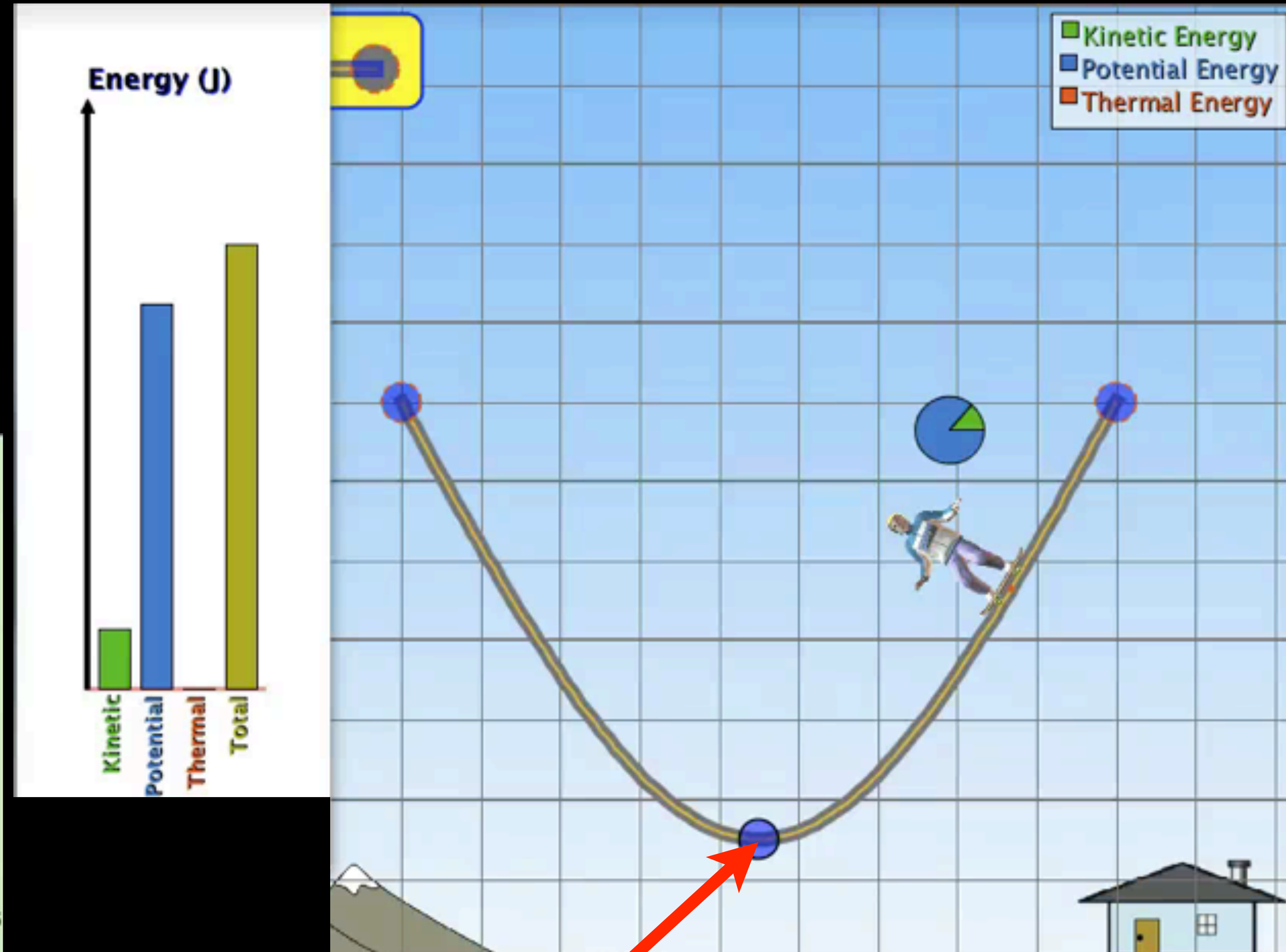
but it can NEVER be destroyed

Energy conservation



Frictionless track

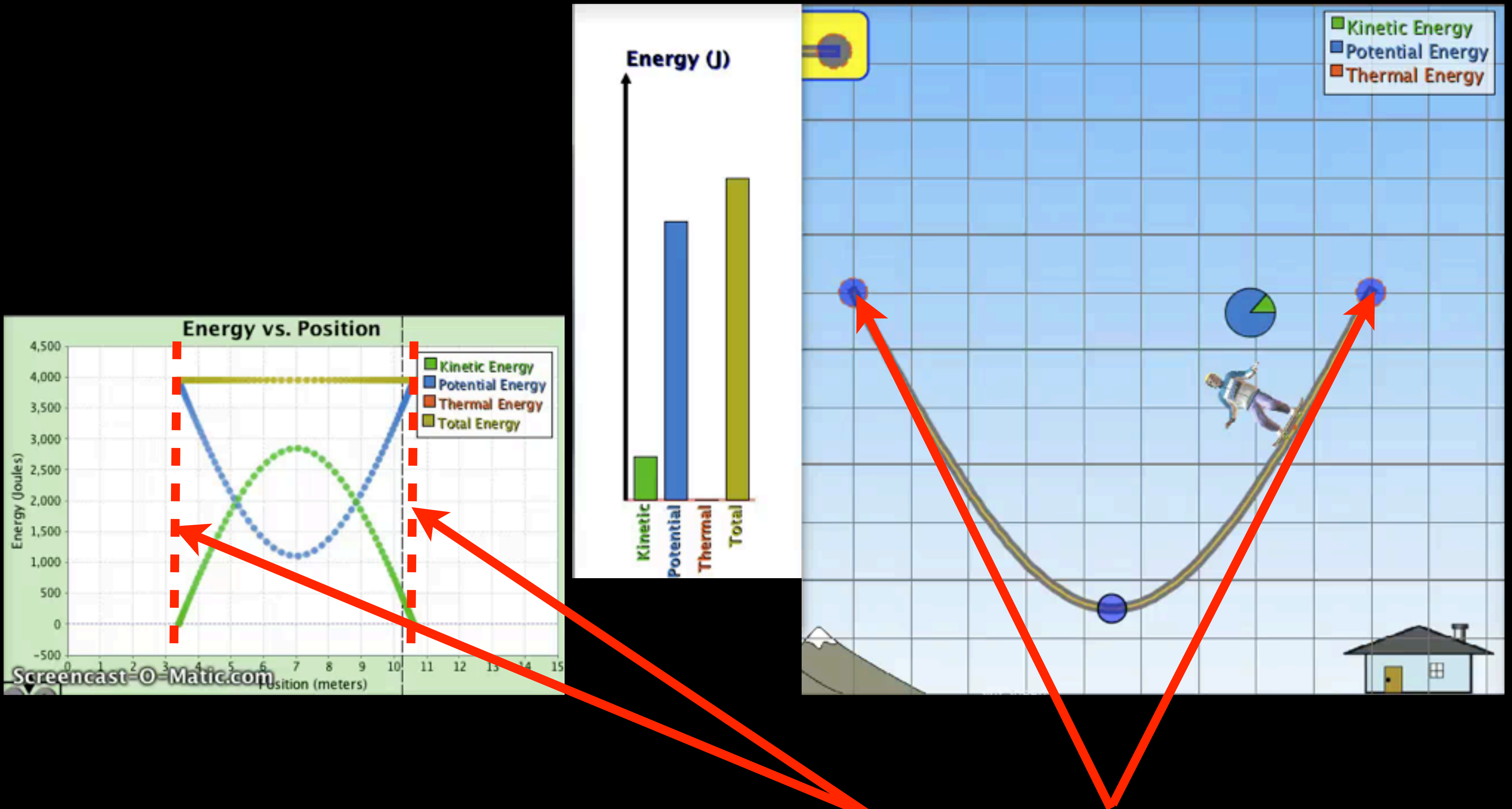




Lowest point

min U

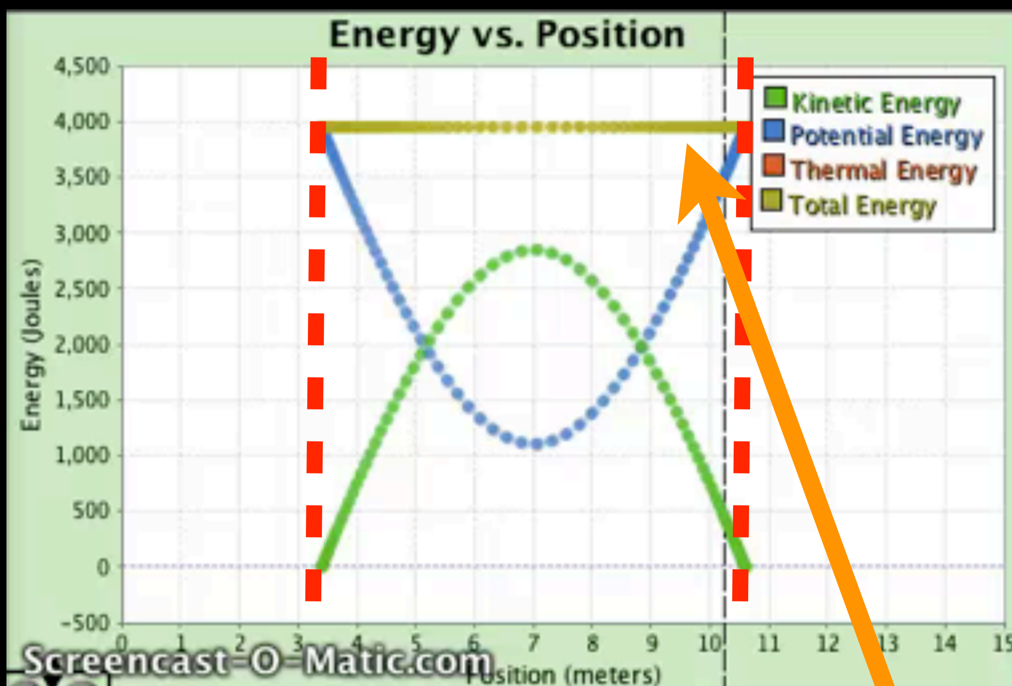
max K

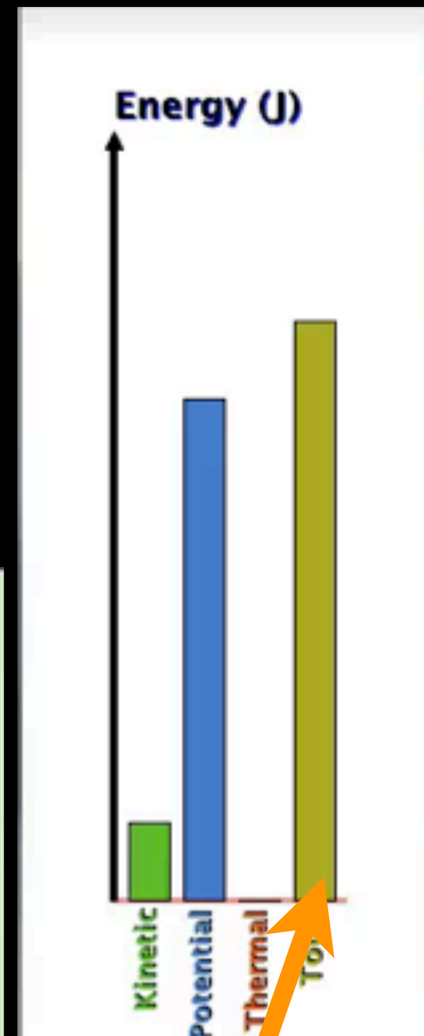


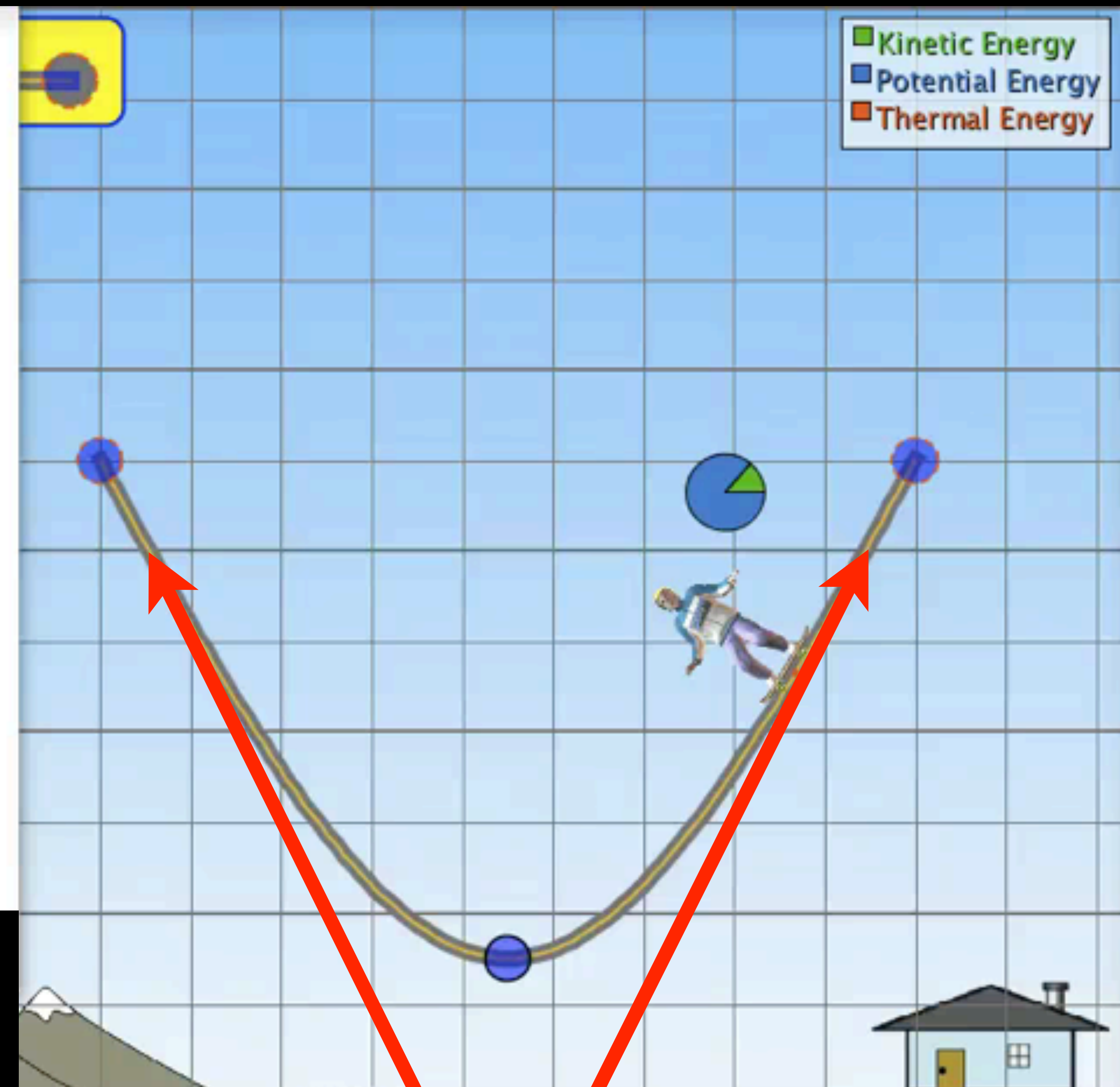
Highest points

max U

min K

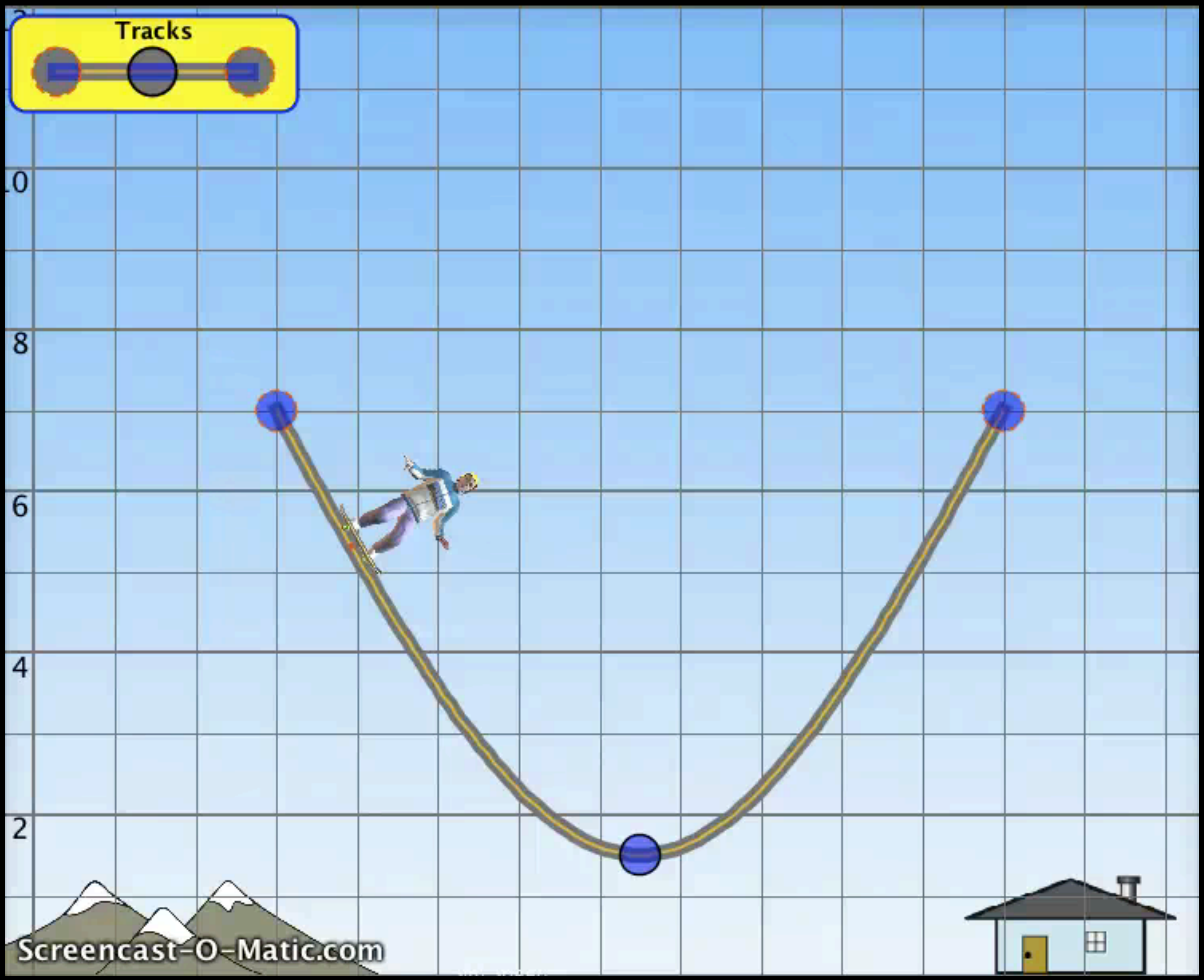






Max height never changes

Total energy is constant



Potential energy

↓

Kinetic energy

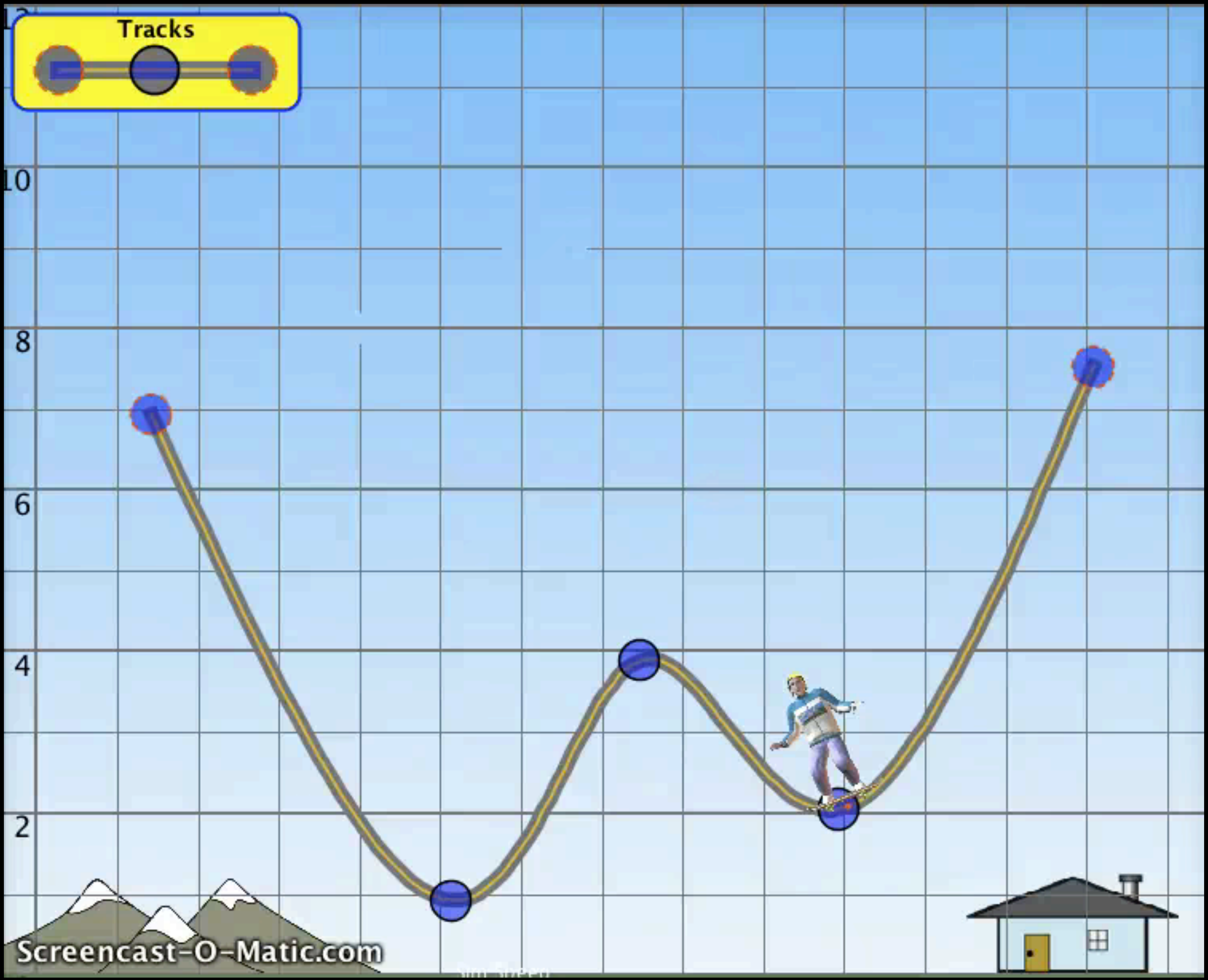
↓

Potential energy

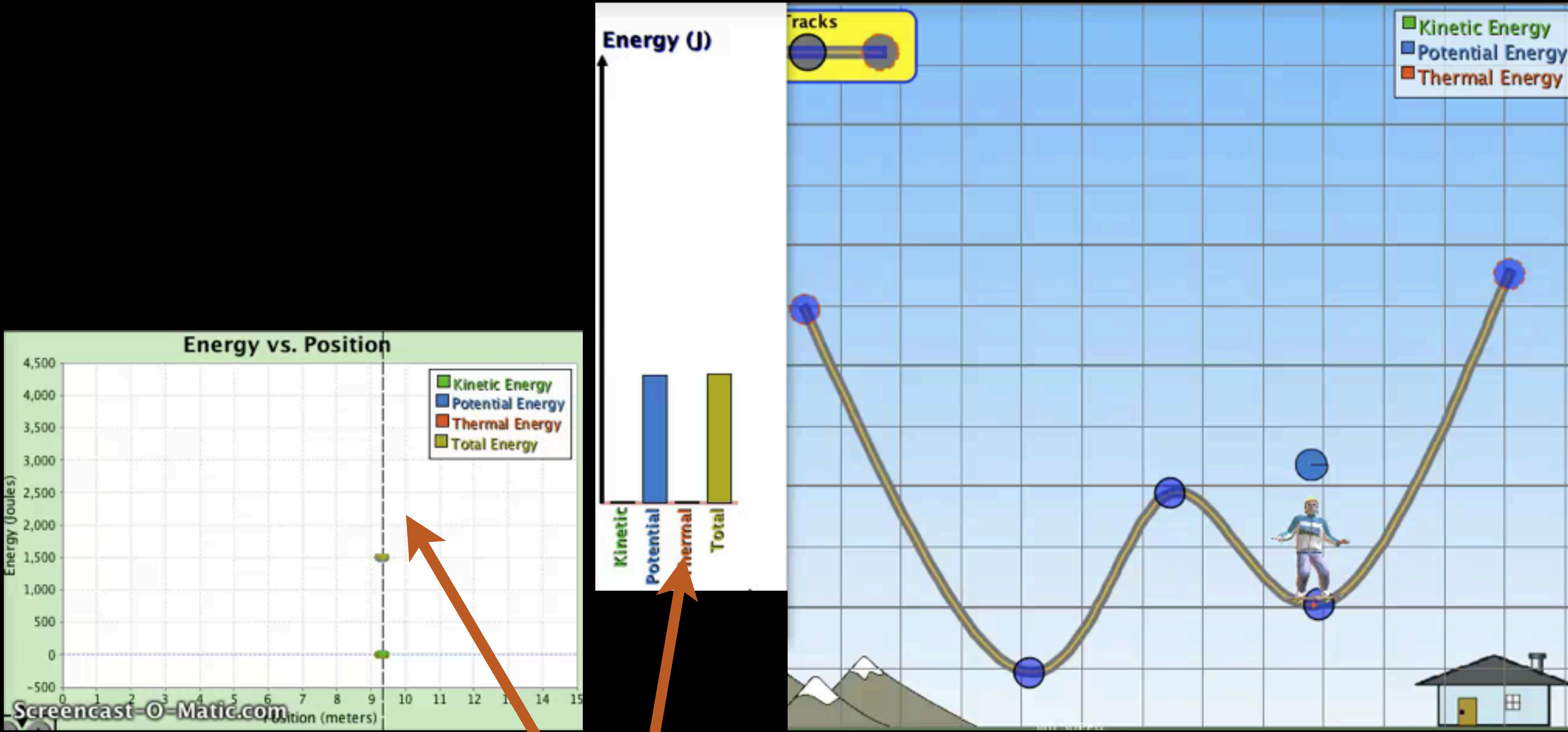
↓

Kinetic energy

⋮

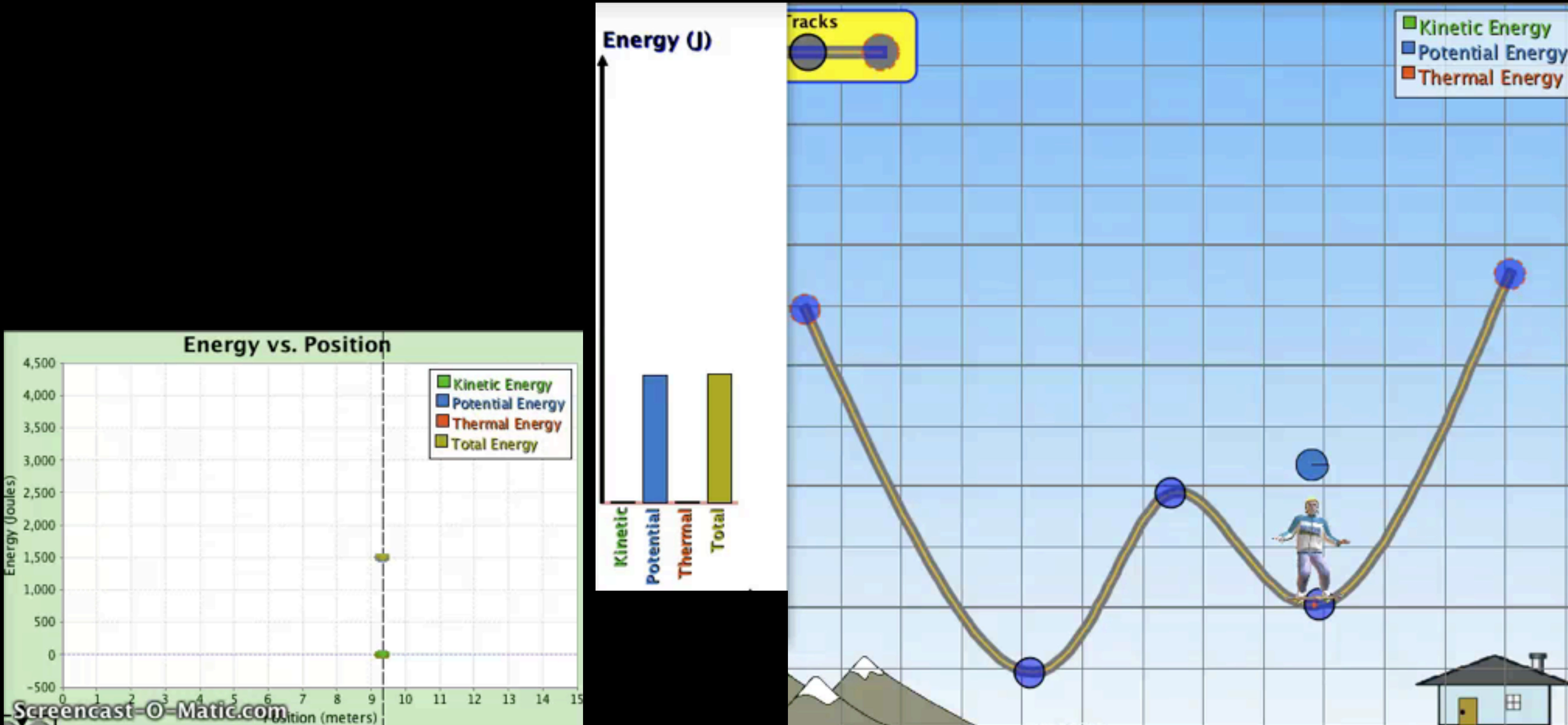


What about this track?



Initially all energy is potential energy, U, and starts to change to K

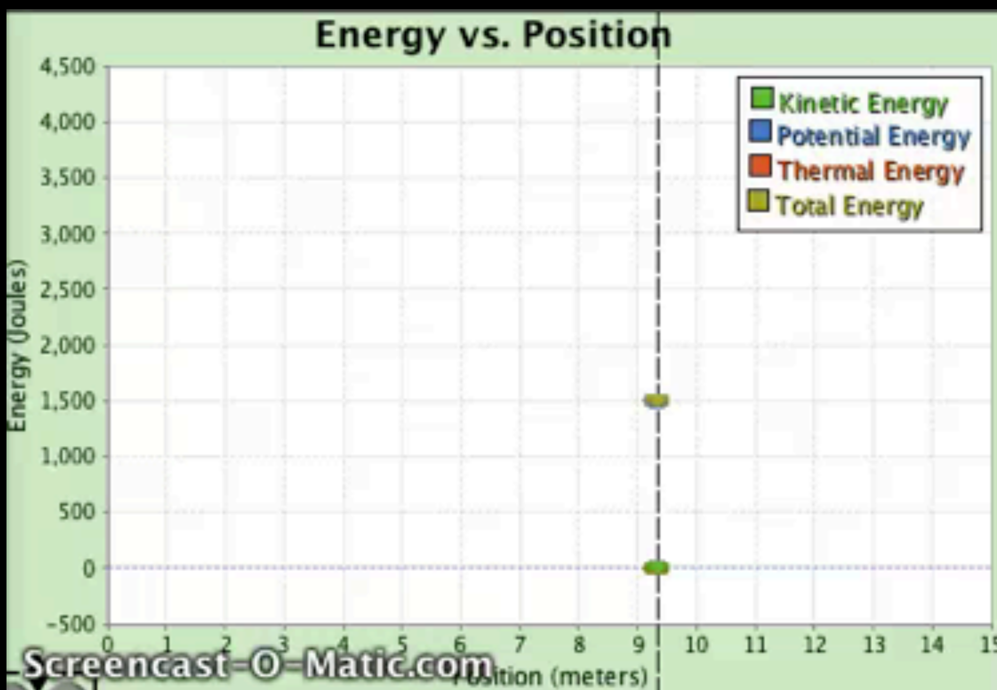
The track impacts create thermal energy (heat)

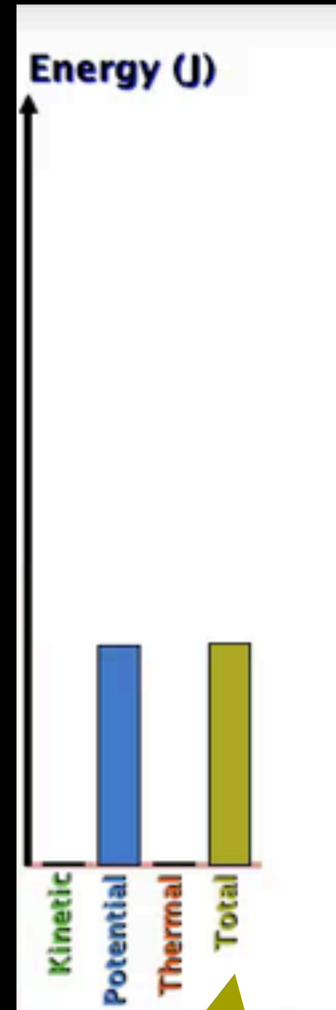


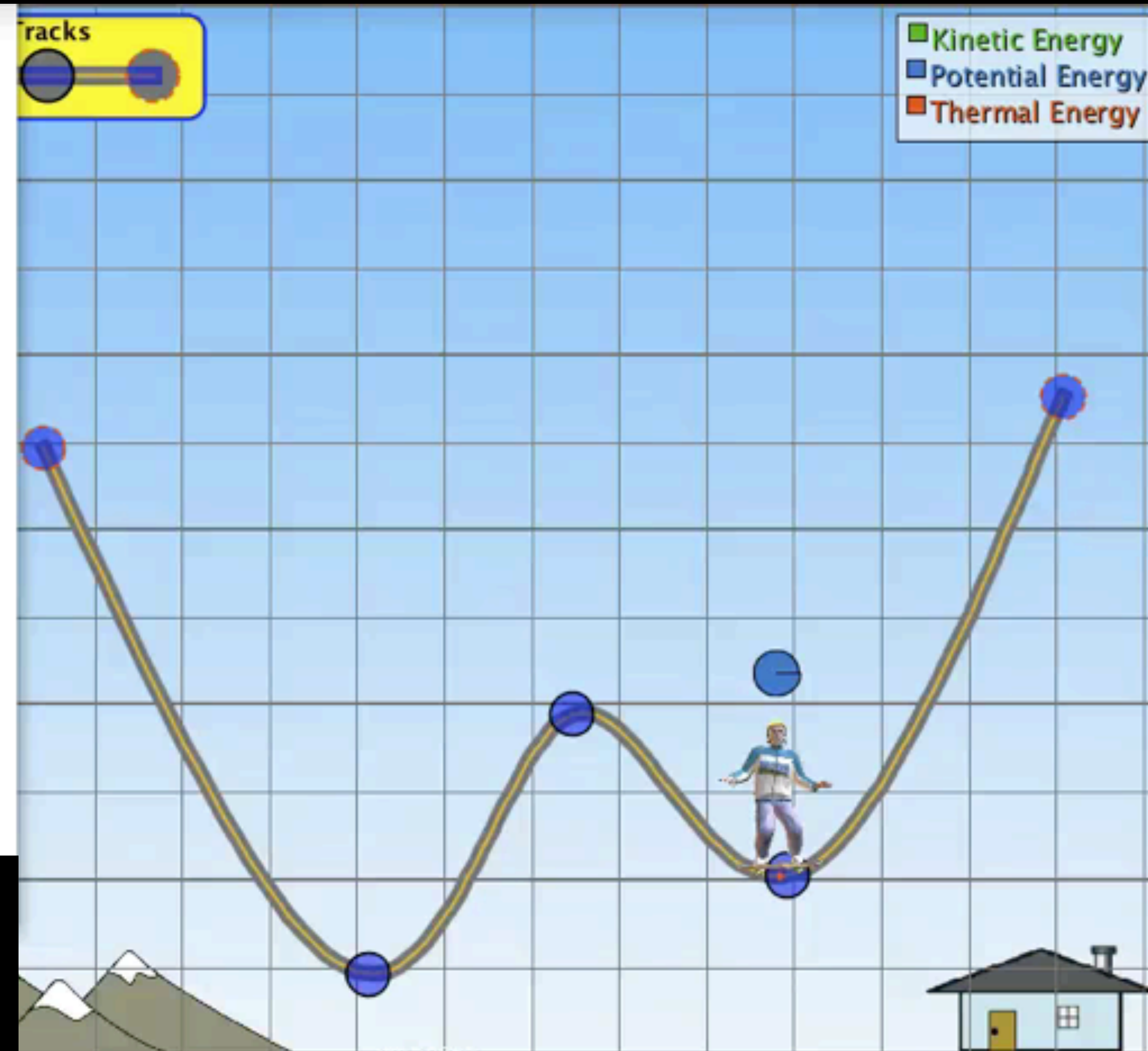
Initially all energy is potential energy, U, and starts to change to K

The track impacts create thermal energy (heat)

Less energy is shared between U and K







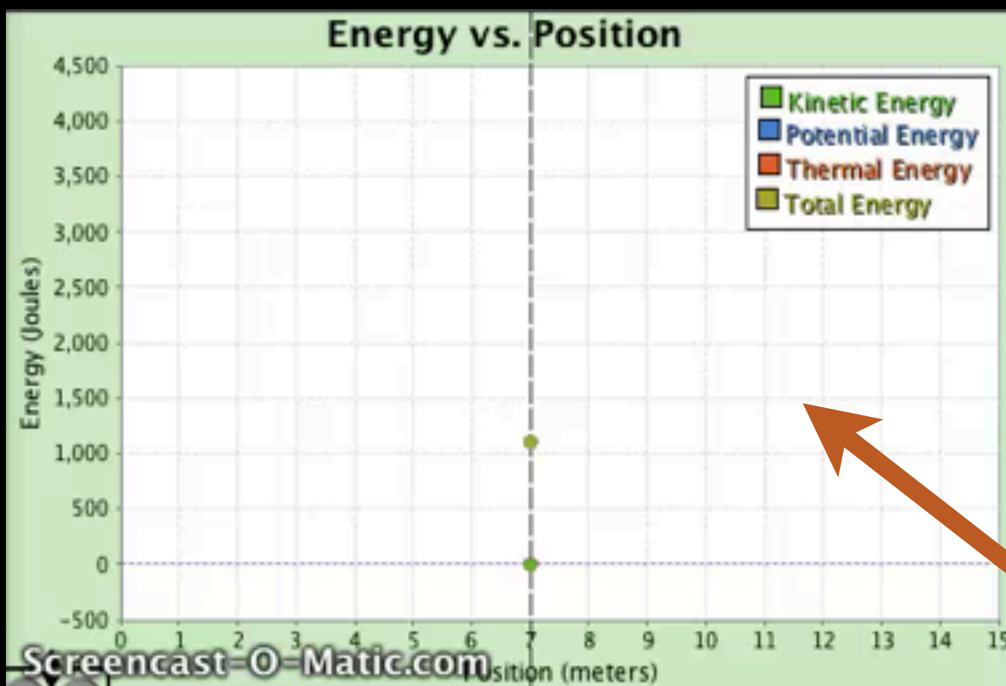
Initially all energy is potential energy, U, and starts to change to K

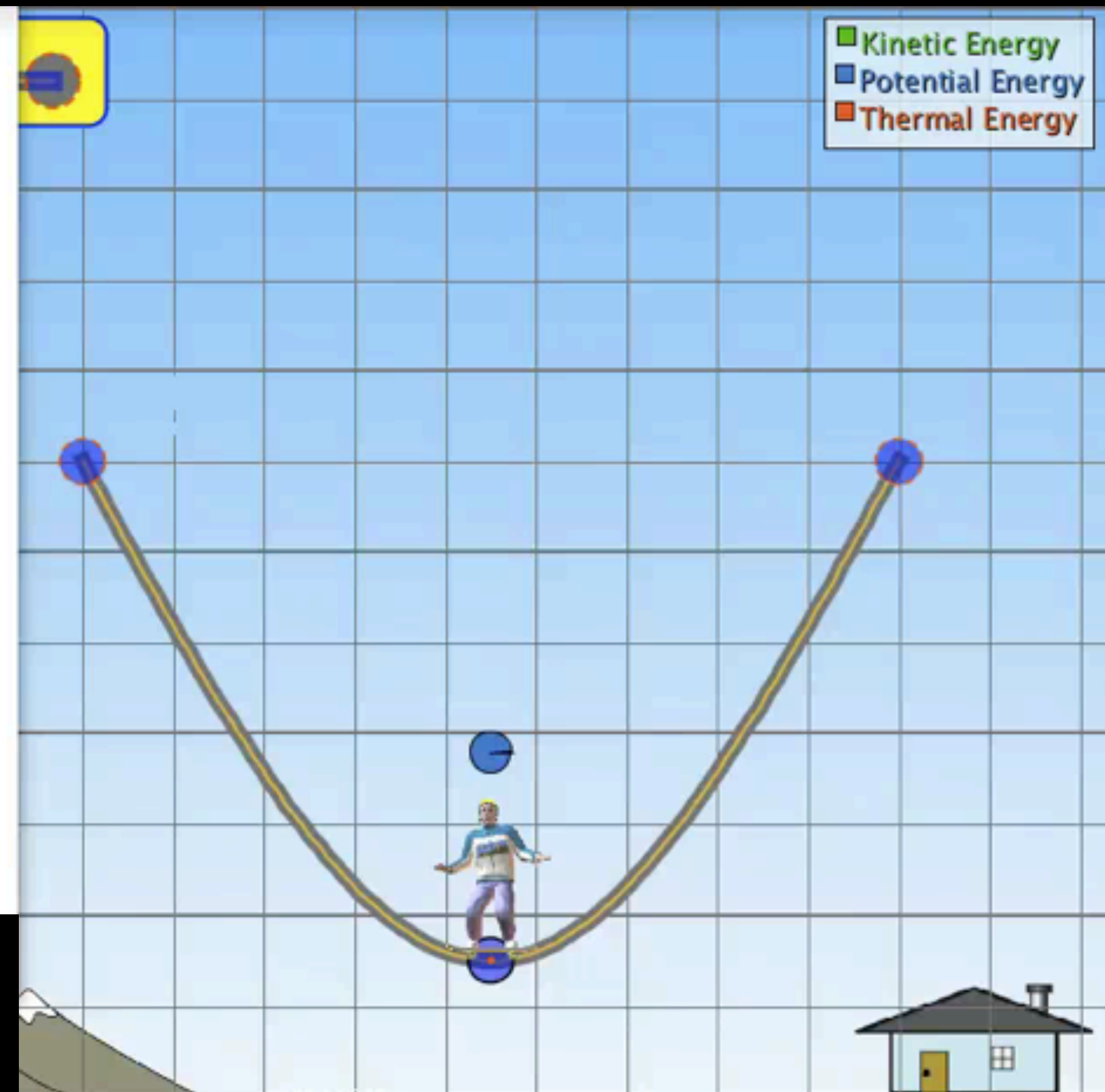
The track impacts create thermal energy (heat)

Less energy is shared between U and K

Total energy is constant (can never destroy energy)

What if we add friction to the track?





Friction creates thermal energy

The more the skater moves, the more thermal energy is generated

Less and less energy is available for K and U

Total energy is constant

Energy conservation

Quiz

When an object is acted on by only conservative forces, the sum of its kinetic and potential energies does not change.

(a) True

(b) False

Energy conservation

Quiz

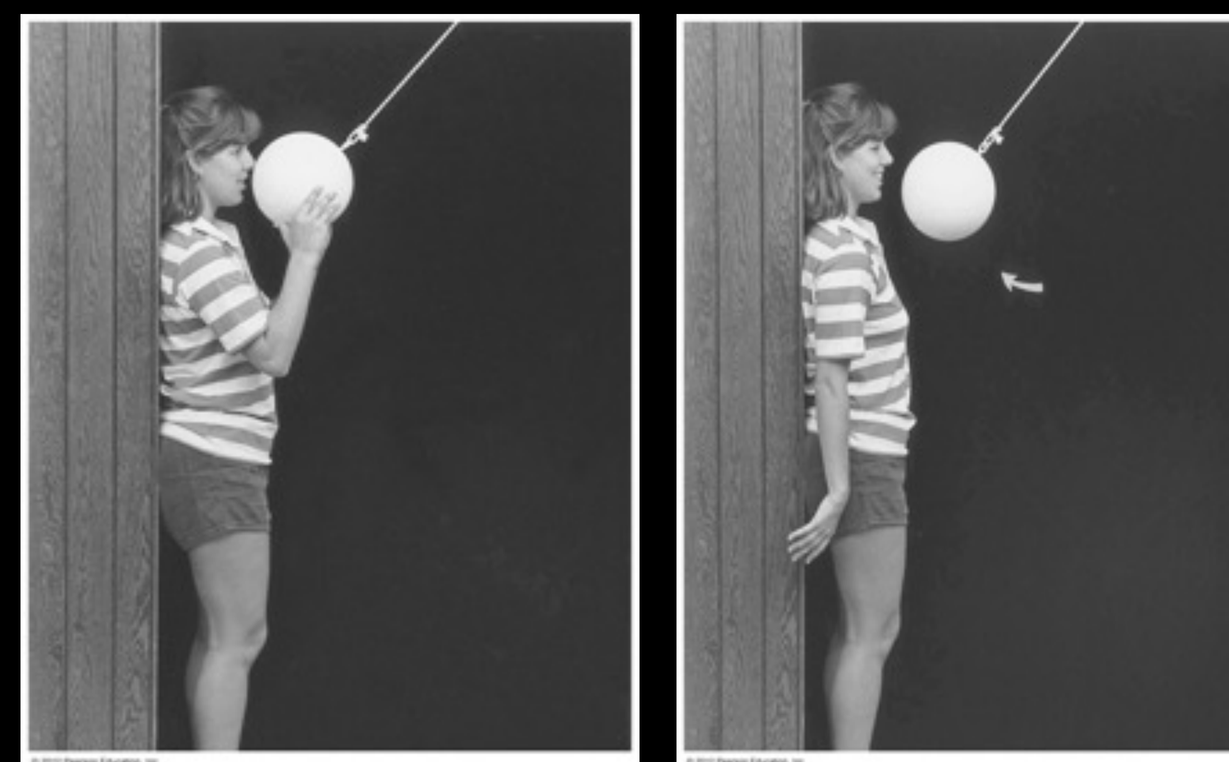
A bowling ball is tied to a rope and hangs from the ceiling.

A girl holds the ball to her nose and releases it.

Should she duck as it swings back?

(a) Yes!

(b) No!



Energy conservation

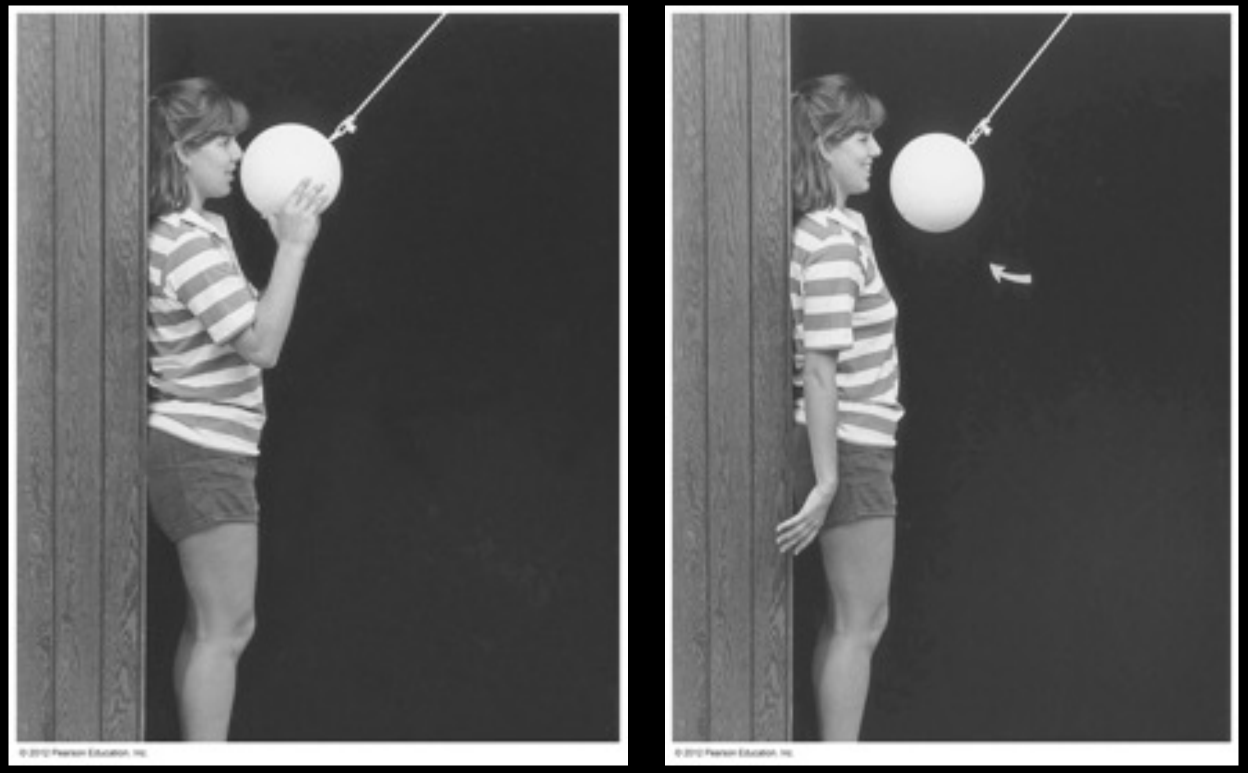
Quiz

If the ball was in a vacuum…

Should she duck?

(a) Yes!

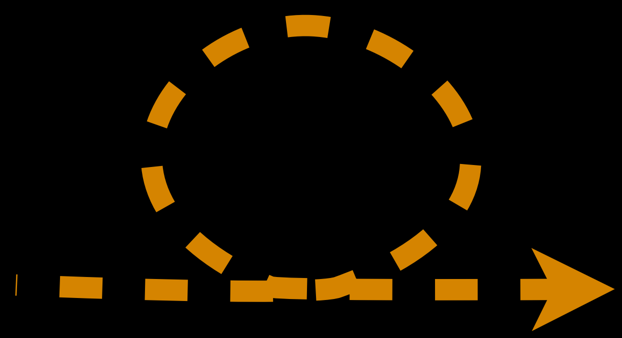
(b) No!

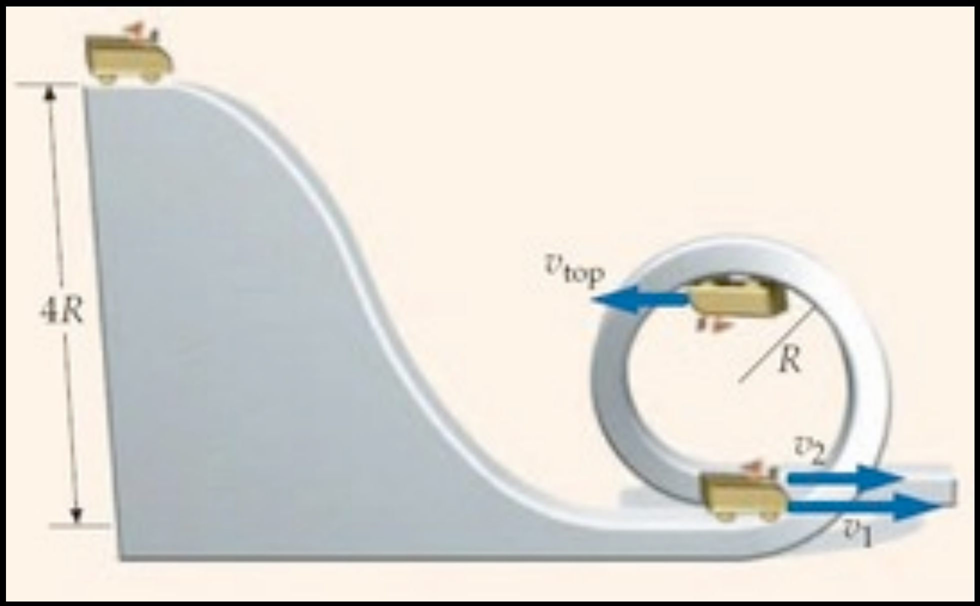


Cannot gain MORE energy than you begin with

Energy conservation — example

What height must the cart start to complete the loop-the-loop?

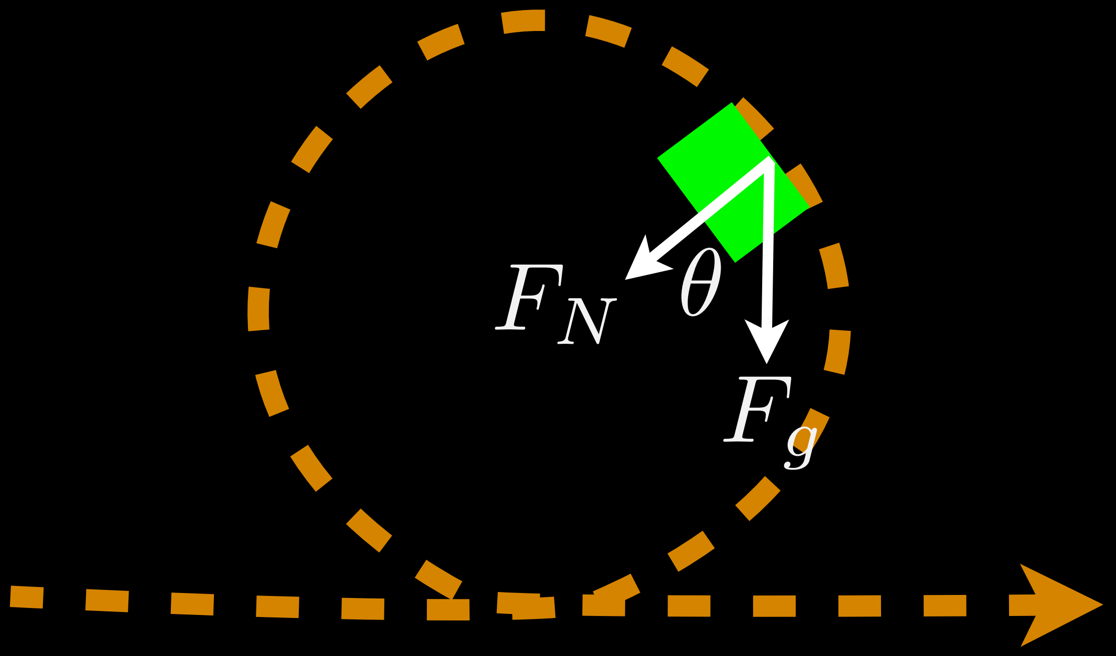




To stay on the track: $F_N > 0$

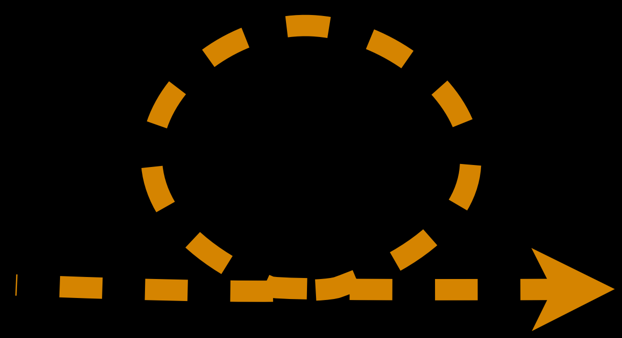
$$\bar{F}_N + \bar{F}_g = m\bar{a}$$

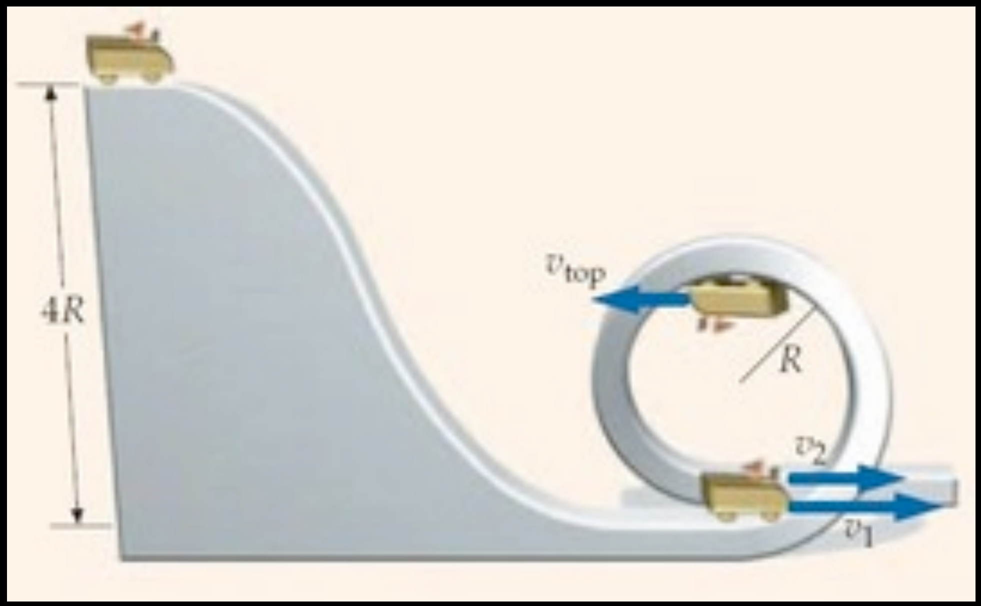
$$F_N + mg\cos\theta = m\frac{v^2}{r}$$



Energy conservation example

What height must the cart start to complete the loop-the-loop?





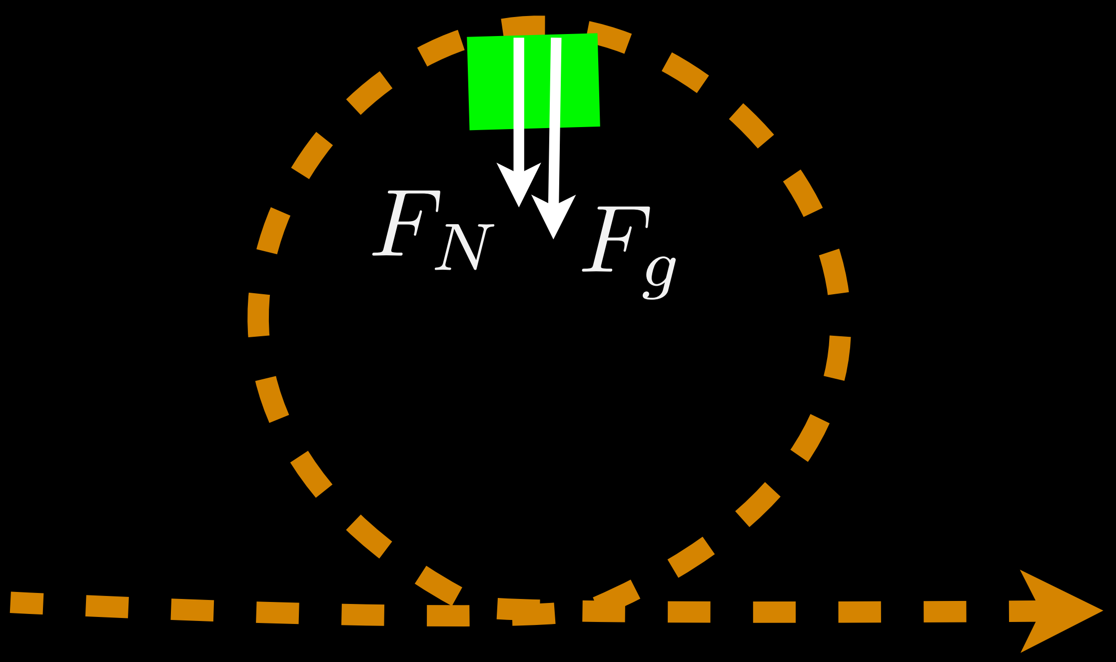
To stay on the track: $F_N > 0$

$$\bar{F}_N + \bar{F}_g = m\bar{a}$$

$$F_N + mg\cos\theta = m\frac{v^2}{r}$$

At loop top: $F_N + mg = m\frac{v^2}{r}$

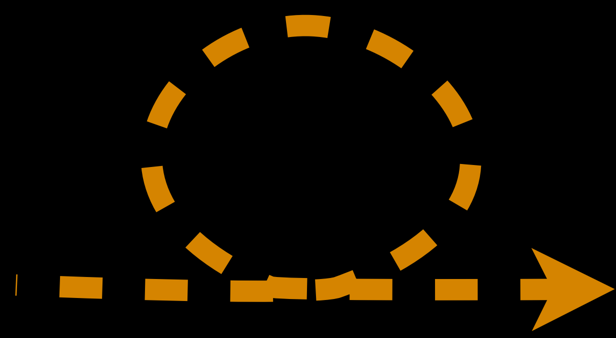
$\xrightarrow{F_N = 0}$ $v_{\min} = \sqrt{rg}$

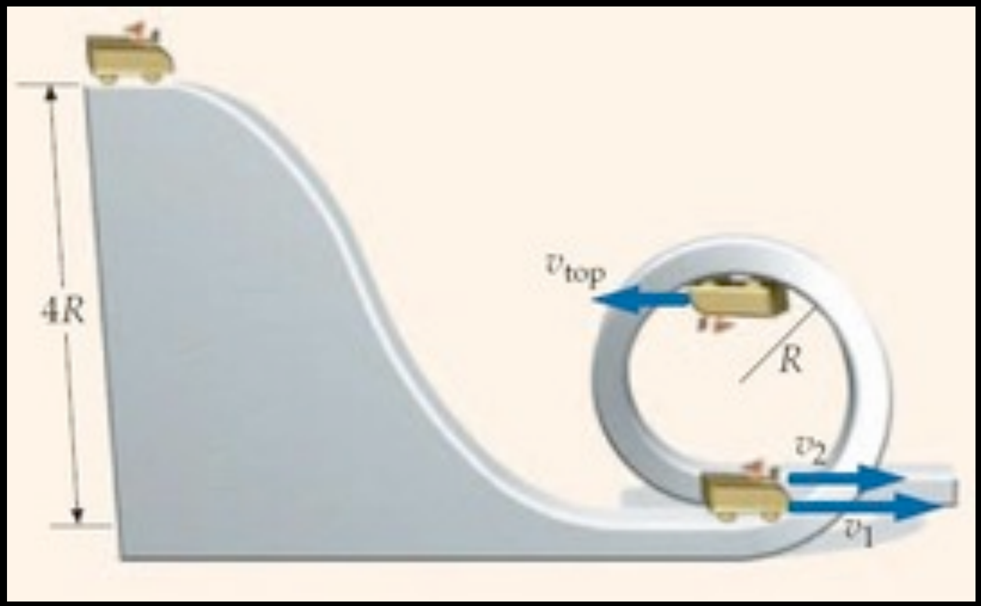


Energy conservation

example

What height must the cart start to complete the loop-the-loop?



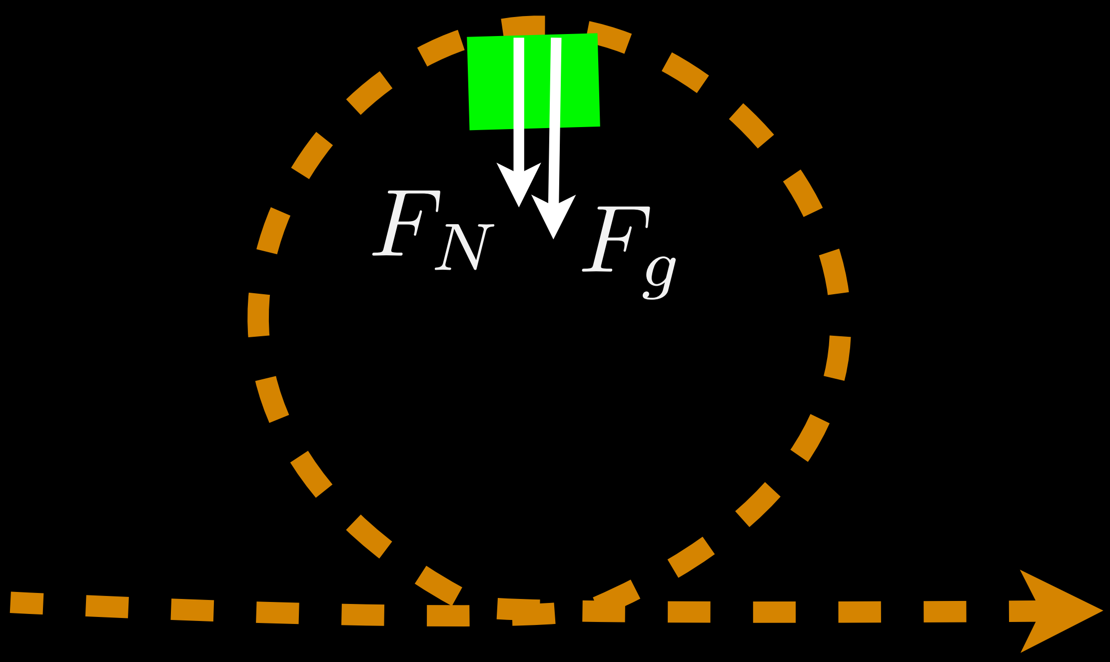


Energy:

$$K_{\text{top}} = \frac{1}{2}mv_{\text{top}}^2 \quad = \frac{1}{2}m(rg)$$

$$U_{\text{top}} = mg2r$$

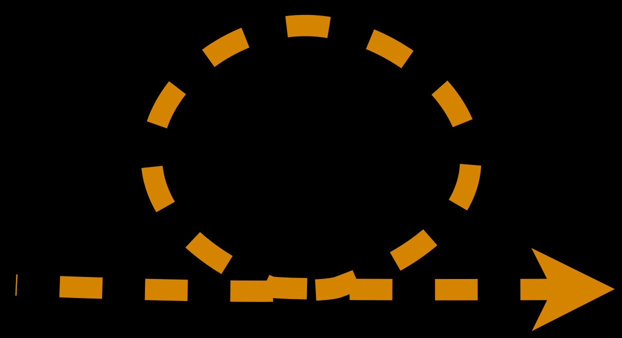
$$E_{\text{top,total}} = \frac{1}{2}mgr + 2mgr$$

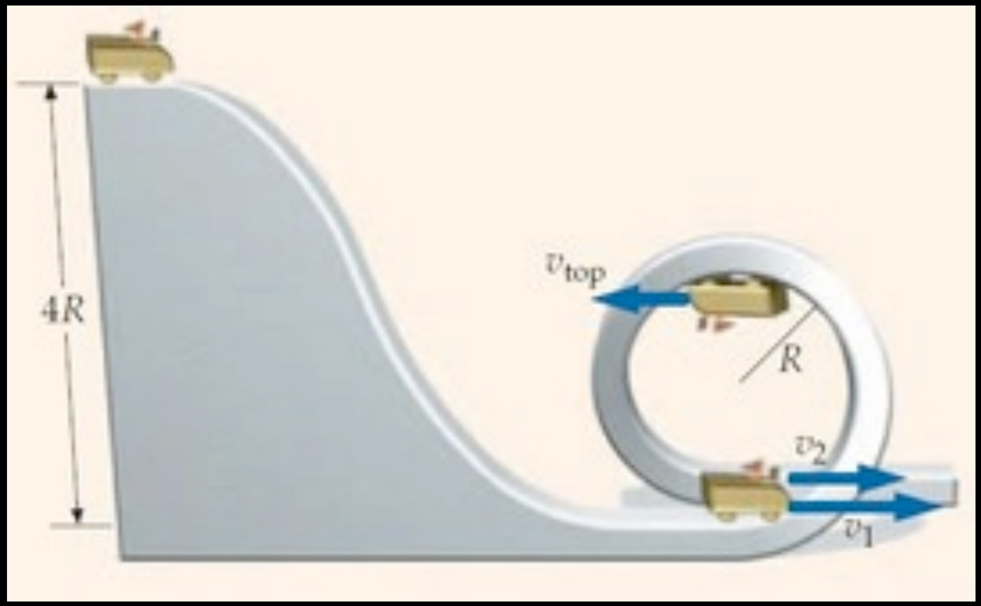


Energy conservation

example

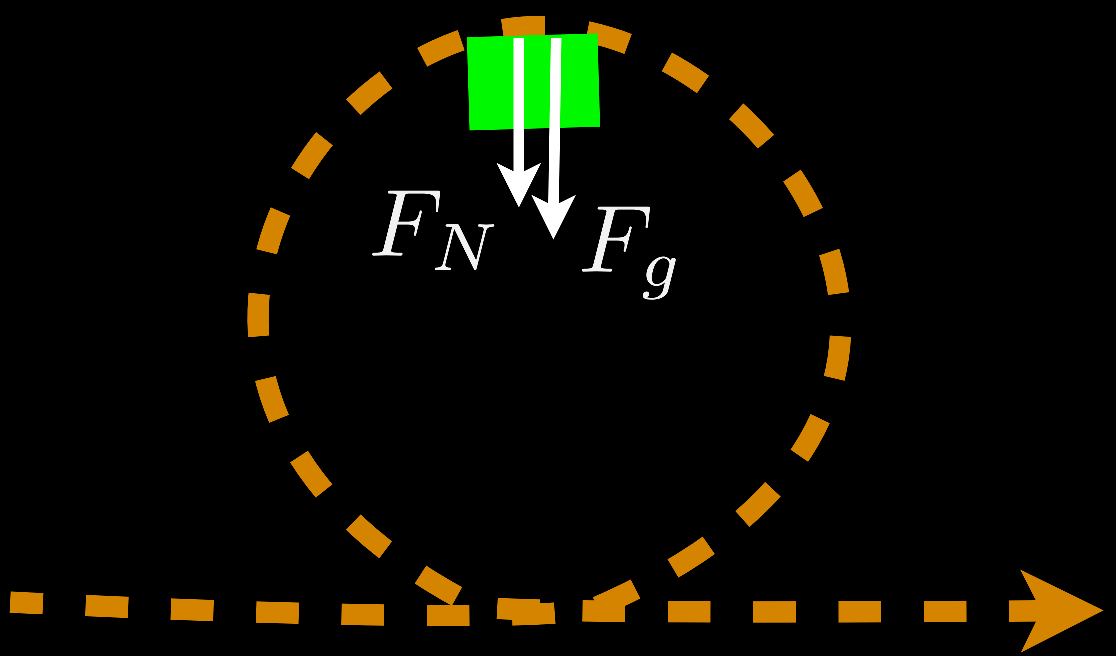
What height must the cart start to complete the loop-the-loop?





Energy conservation:

$$E_{\text{top,total}} = E_{\text{start}}$$
$$= U_{\text{start}} + K_{\text{start}}(= 0)$$
$$= mg\Delta h$$
$$\frac{5}{2}mgr = mg\Delta h$$
$$\Delta h = \frac{5}{2}r$$



Energy conservation

Quiz

A block is launched up a frictionless slope at 40 degrees, with speed v. It reaches a vertical height h.

Speed is changed to 2v. What is the new height?

(a) h

(b) h/2

(c) 2h

(d) 4h

(e) 8h

Energy conservation

Quiz

A block is launched up a frictionless slope at 40 degrees, with speed v. It reaches a vertical height h.

Speed is changed to 2v. What is the new height?

$$KE \to U \qquad \frac{1}{2}mv^2 = mgh \longrightarrow h = \frac{v^2}{2g}$$

$$\frac{1}{2}m(2v)^2 = mgh_2 \longrightarrow h_2 = \frac{(2v)^2}{2g} = 4h$$

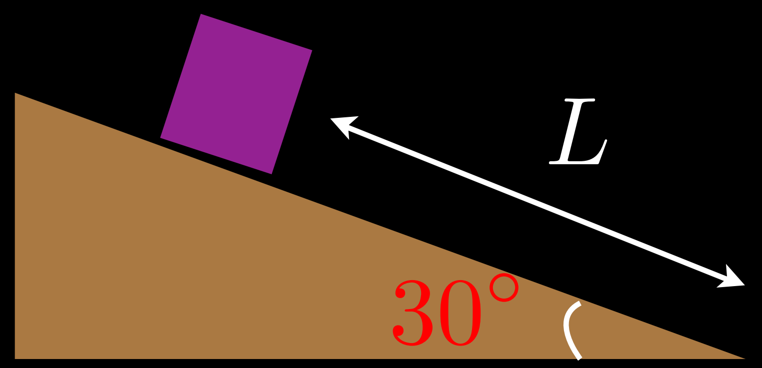
Energy conservation

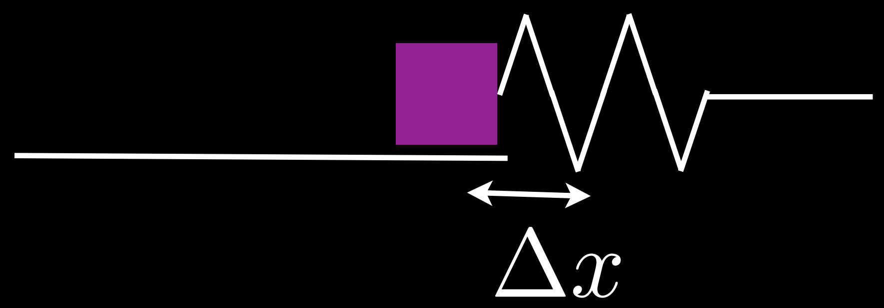
Quiz

A 1 kg block slides 4m down a frictionless plane inclined at 30° to the horizontal.

After reaching the bottom, it slides along a frictionless horizontal plane and strikes a spring with constant k = 314 N/m.

How far is the spring compressed when it stops the block?



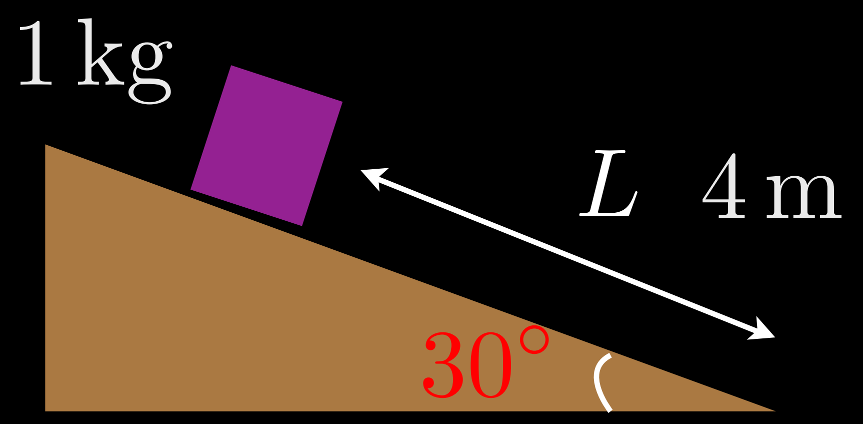


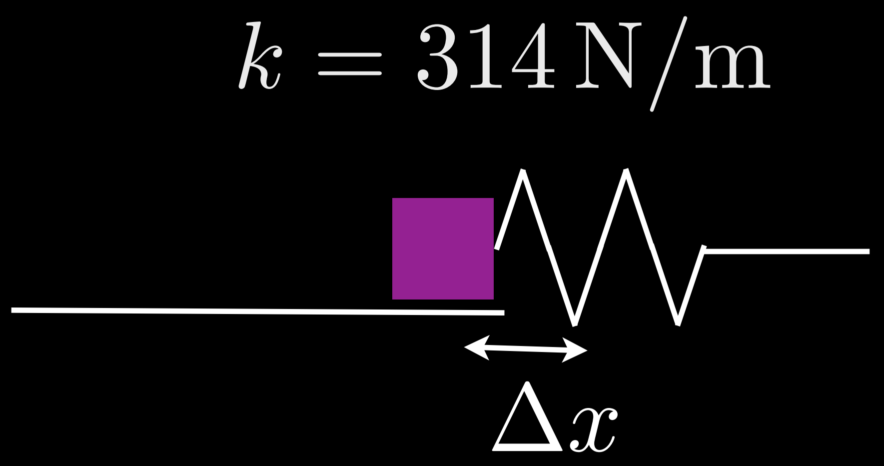
Energy conservation:

$$U_{\text{slope}} \rightarrow K_{\text{block}} \rightarrow U_{\text{spring}}$$

Energy conservation

Quiz





(a) 35 cm

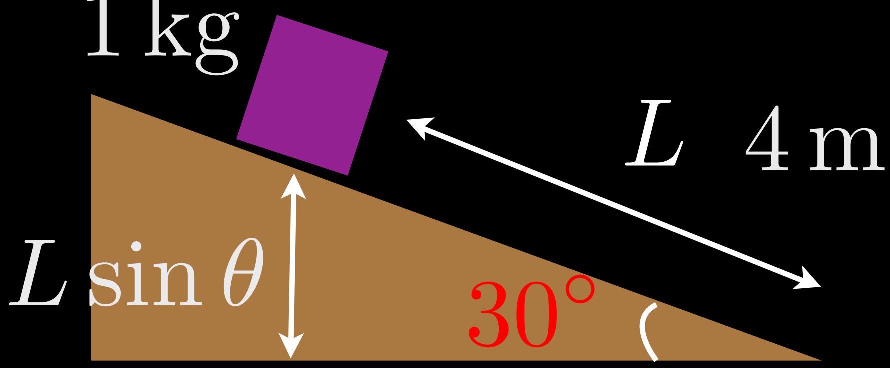
(b) 50 cm

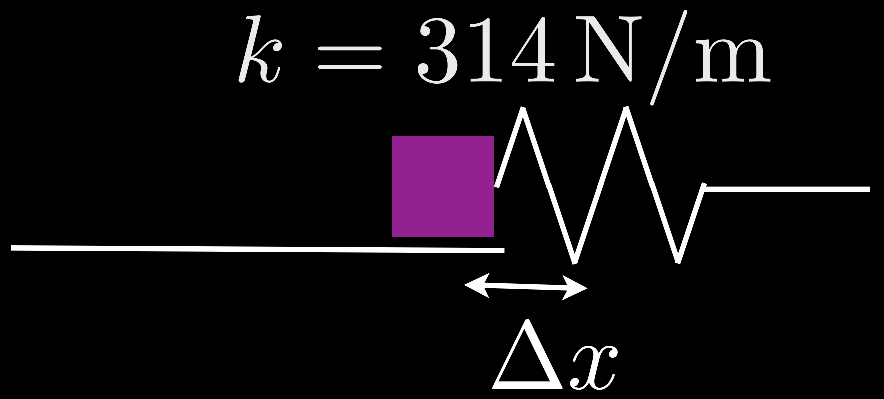
(c) 0.4 cm

(d) 29 cm

Energy conservation

Quiz





Energy conservation:

$$U_{\text{slope}} \to K_{\text{block}} \to U_{\text{spring}}$$

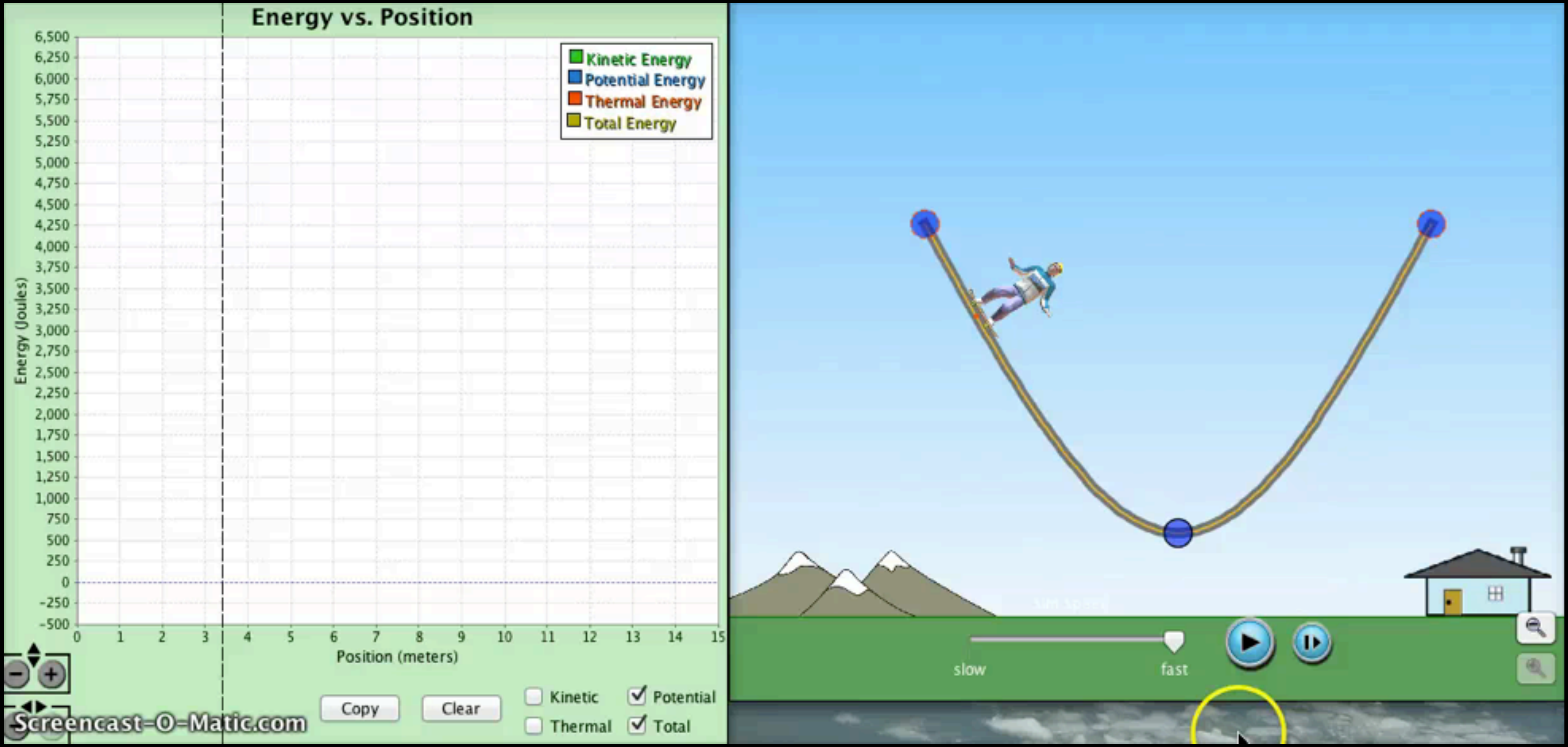
$$U_{\text{slope}} = mgL\sin\theta \;\; = K_{\text{block}}$$

$$K_{\text{block}} = U_{\text{spring}} = \frac{1}{2}kx^2$$

$$\frac{1}{2}kx^2 = mgL\sin\theta$$

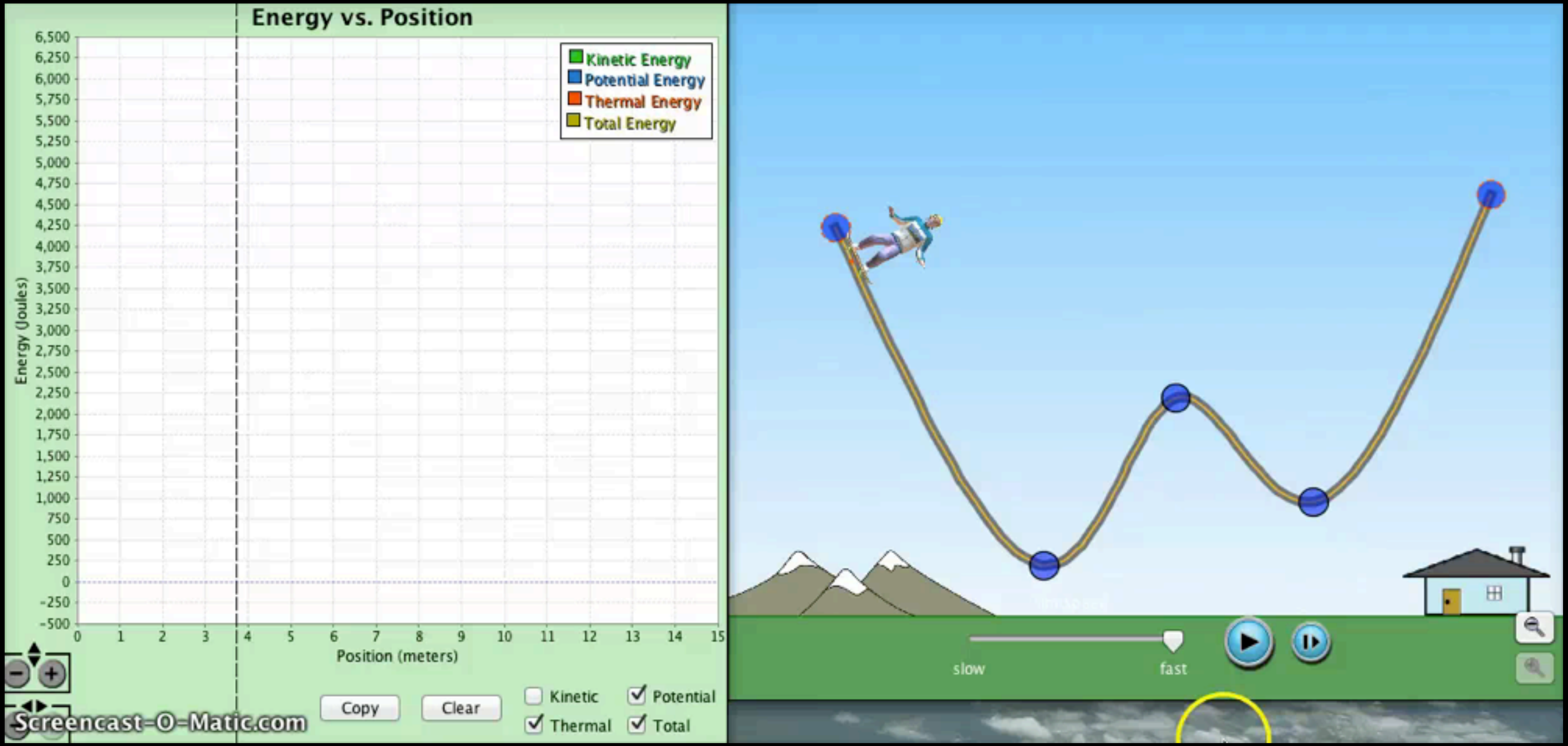
$$x = \sqrt{\frac{2mgL\sin\theta}{k}} = 35\text{cm}$$

Potential energy curve



Potential energy vs position is called a potential energy curve

Potential energy curve



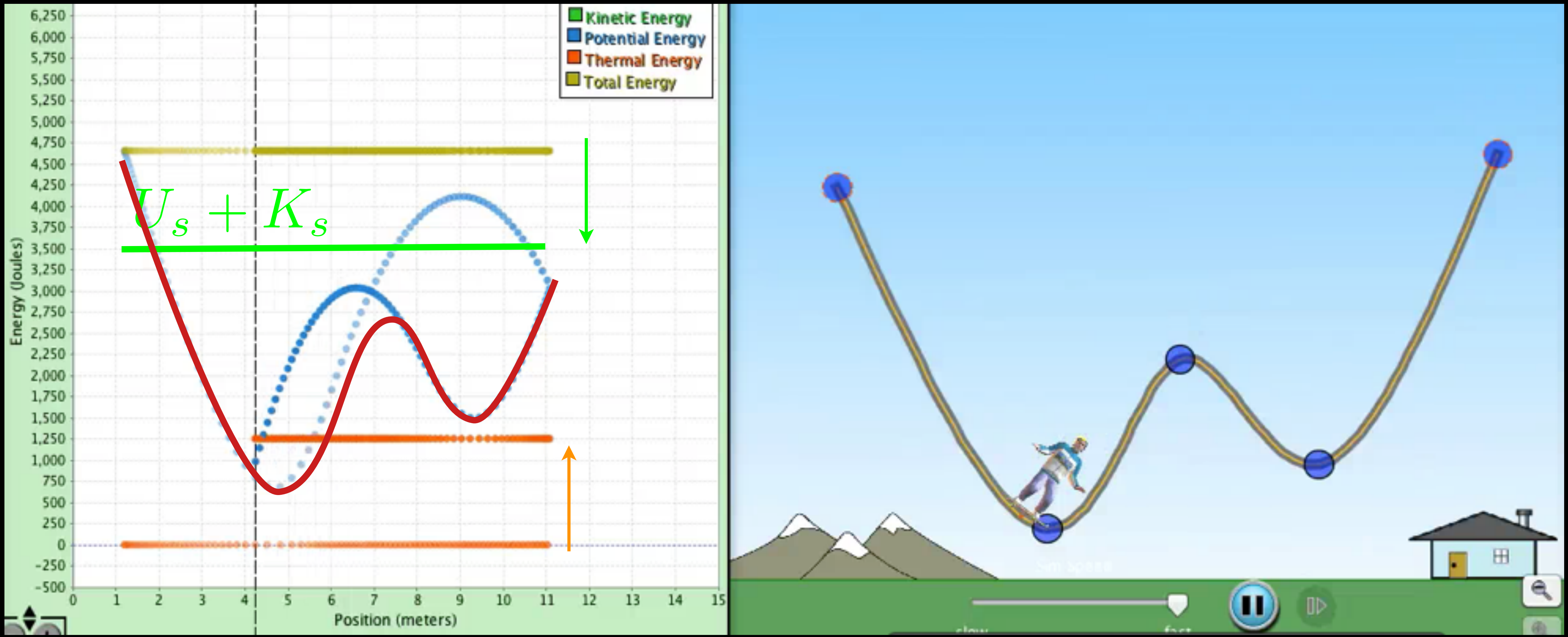
We can use it to understand the skater's motion

Potential energy curve

Initially, the skater's potential + kinetic energy > track's potential:

$U_\mathrm{s} + K_\mathrm{s} > U_\mathrm{T}$

Potential energy curve

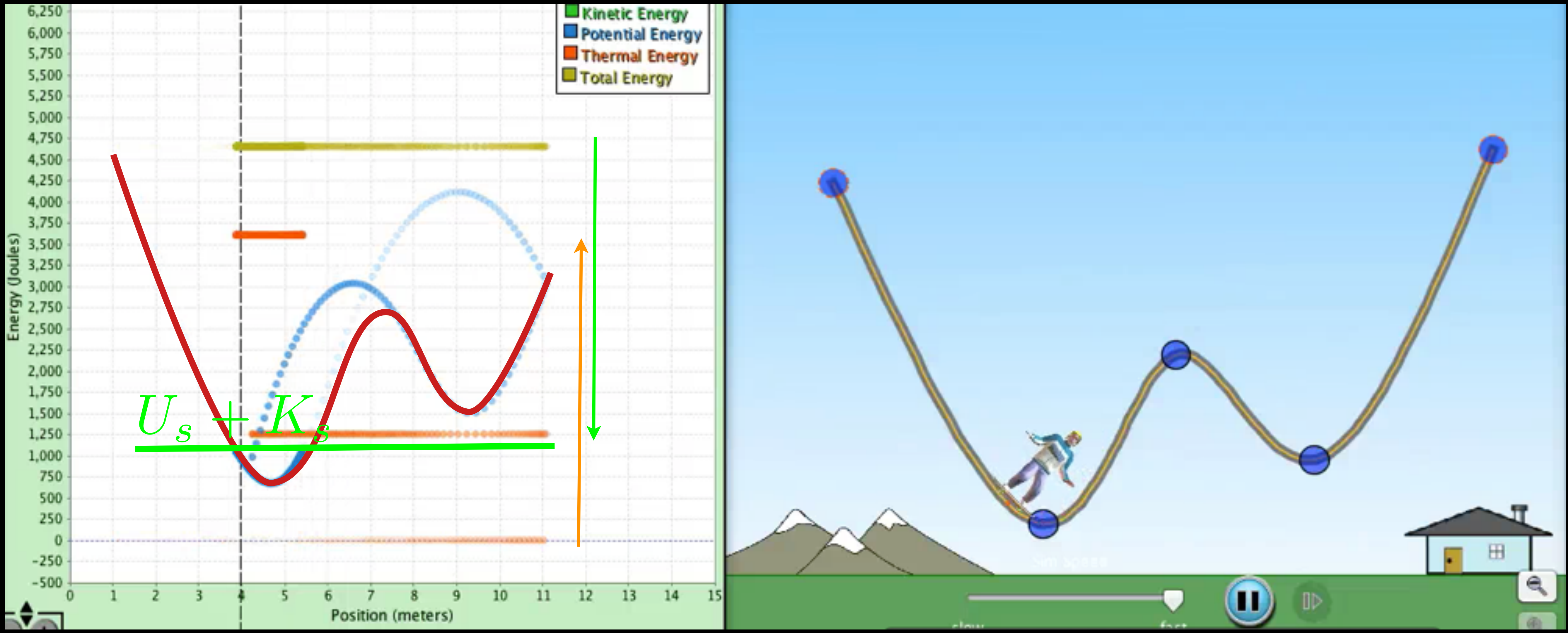


Initially, the skater's potential + kinetic energy > track's potential:
$U_{\rm s} + K_{\rm s} > U_{\rm T}$

Track impact creates thermal energy, decreasing $U_s + K_s$

It is no longer larger than all of the track's potential

Potential energy curve



Initially, the skater's potential + kinetic energy > track's potential: $U_\mathrm{s} + K_\mathrm{s} > U_\mathrm{T}$

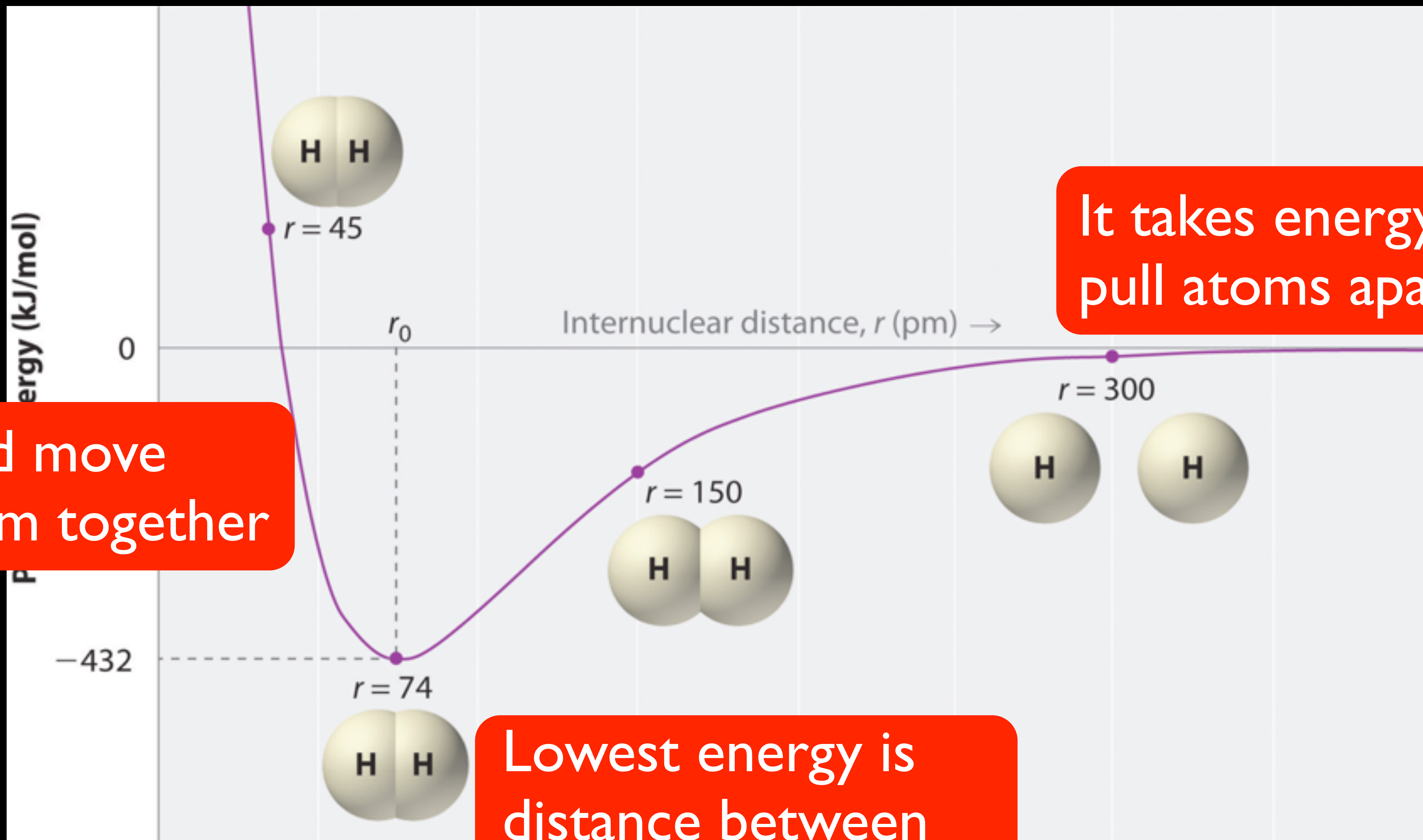
Track impact creates thermal energy, decreasing $U_s + K_s$

It is no longer larger than all of the track's potential

The skater gets trapped in a potential barrier

Potential energy curve

Potential barriers are not just gravity



It takes energy to pull atoms apart

And move them together

Lowest energy is distance between atoms in a molecule

Force and potential energy

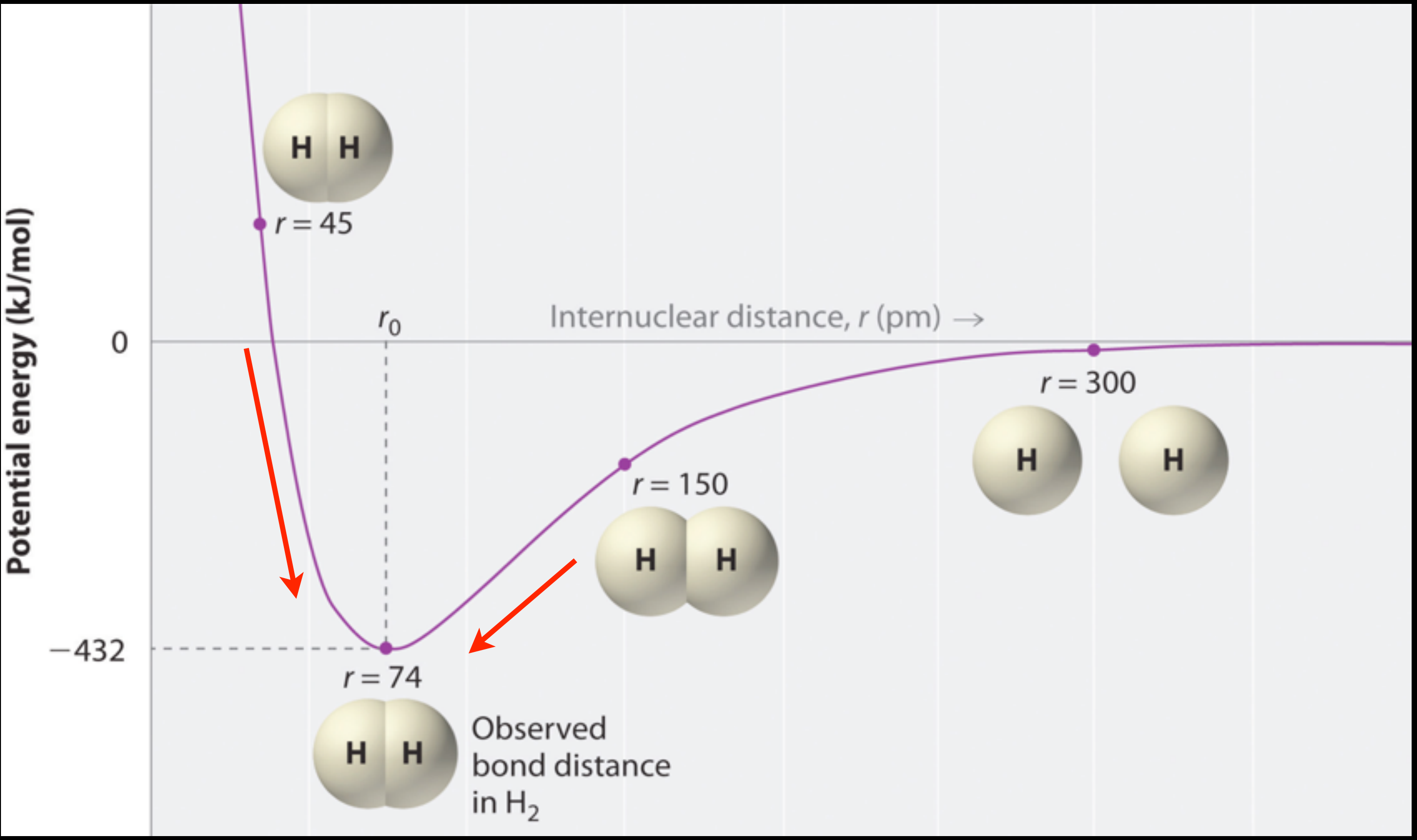
The slope of the potential is the force

In 1D:

$$\Delta U_{AB} = -\int_A^B F_x dx$$

Therefore:

$$F_x = -\frac{dU}{dx}$$

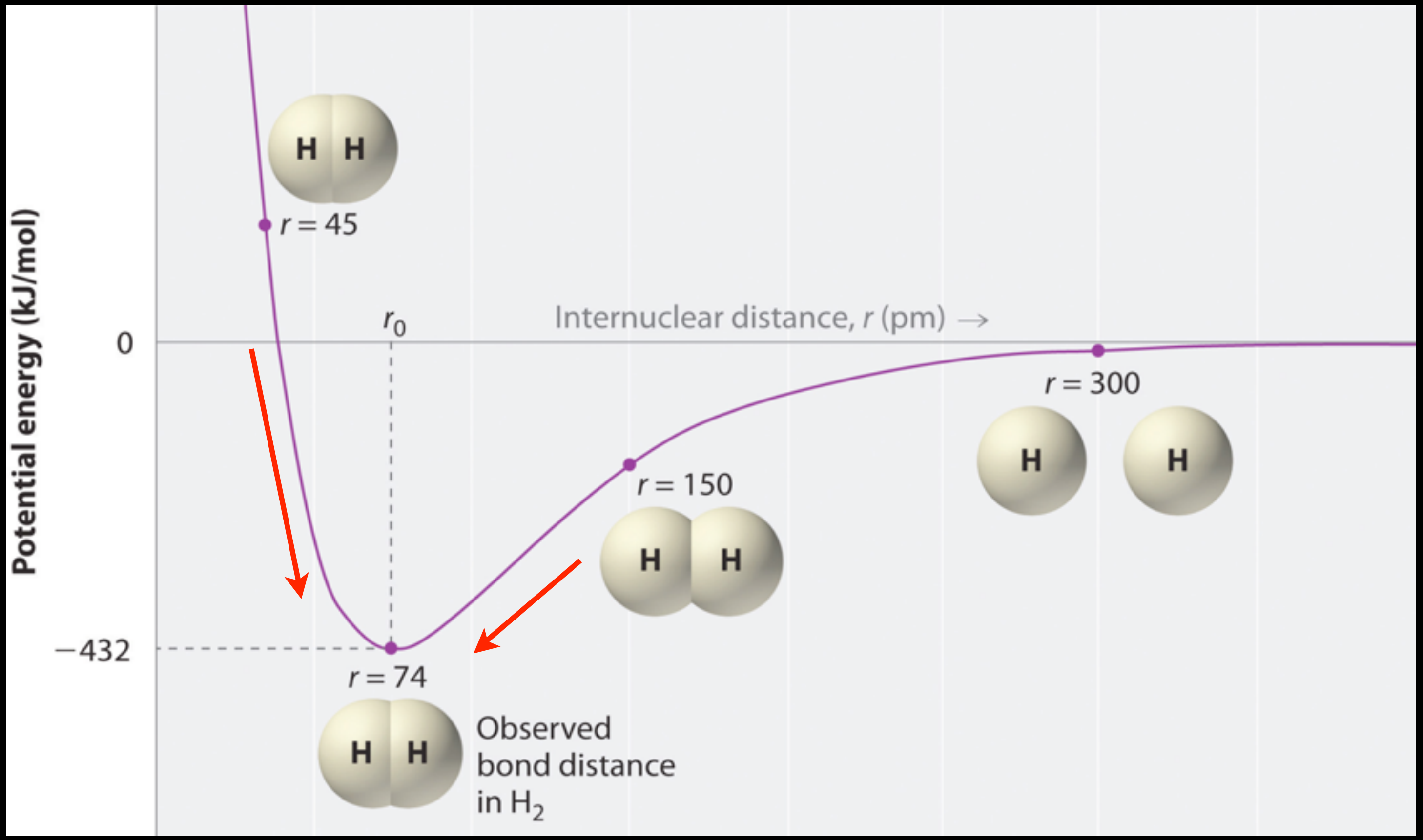


The force acts in the direction of the potential minimum

Force and potential energy

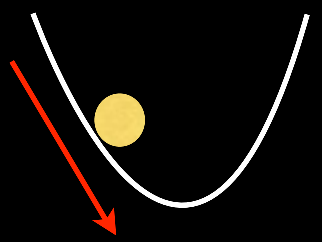
Where the slope is zero, there is no force:

$$-\frac{dU}{dx} = 0 \rightarrow F_x = 0$$

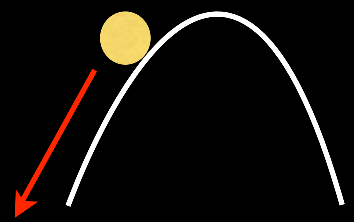


This is called an equilibrium position

If a small displacement creates a force towards the equilibrium position, it is a stable equilibrium.



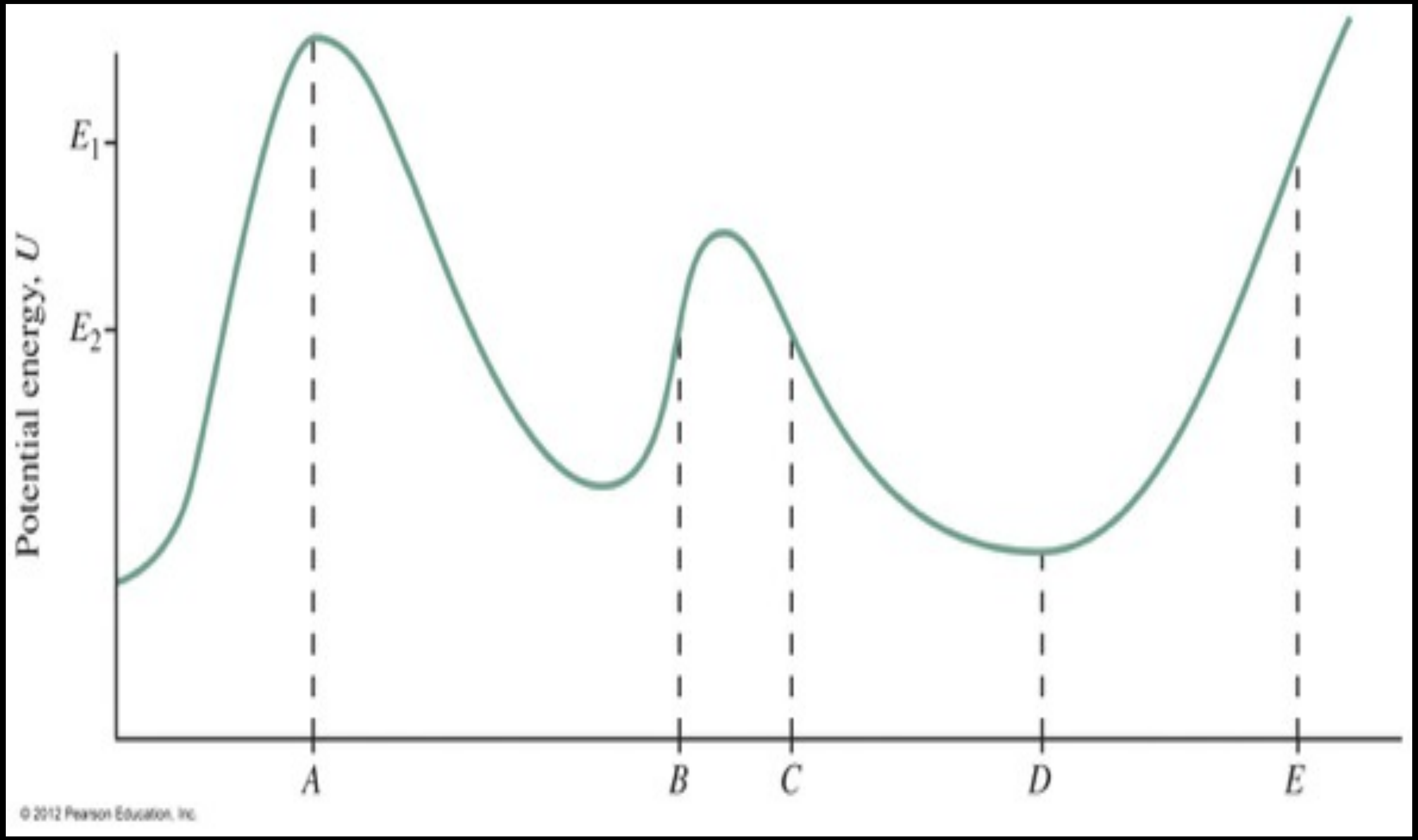
If a small displacement creates a force away the equilibrium position, it is a unstable equilibrium.



Force and potential energy

Quiz

Potential energy for an electron in a microelectronic device



Where is the force greatest?

(a) A

(b) B

(c) C

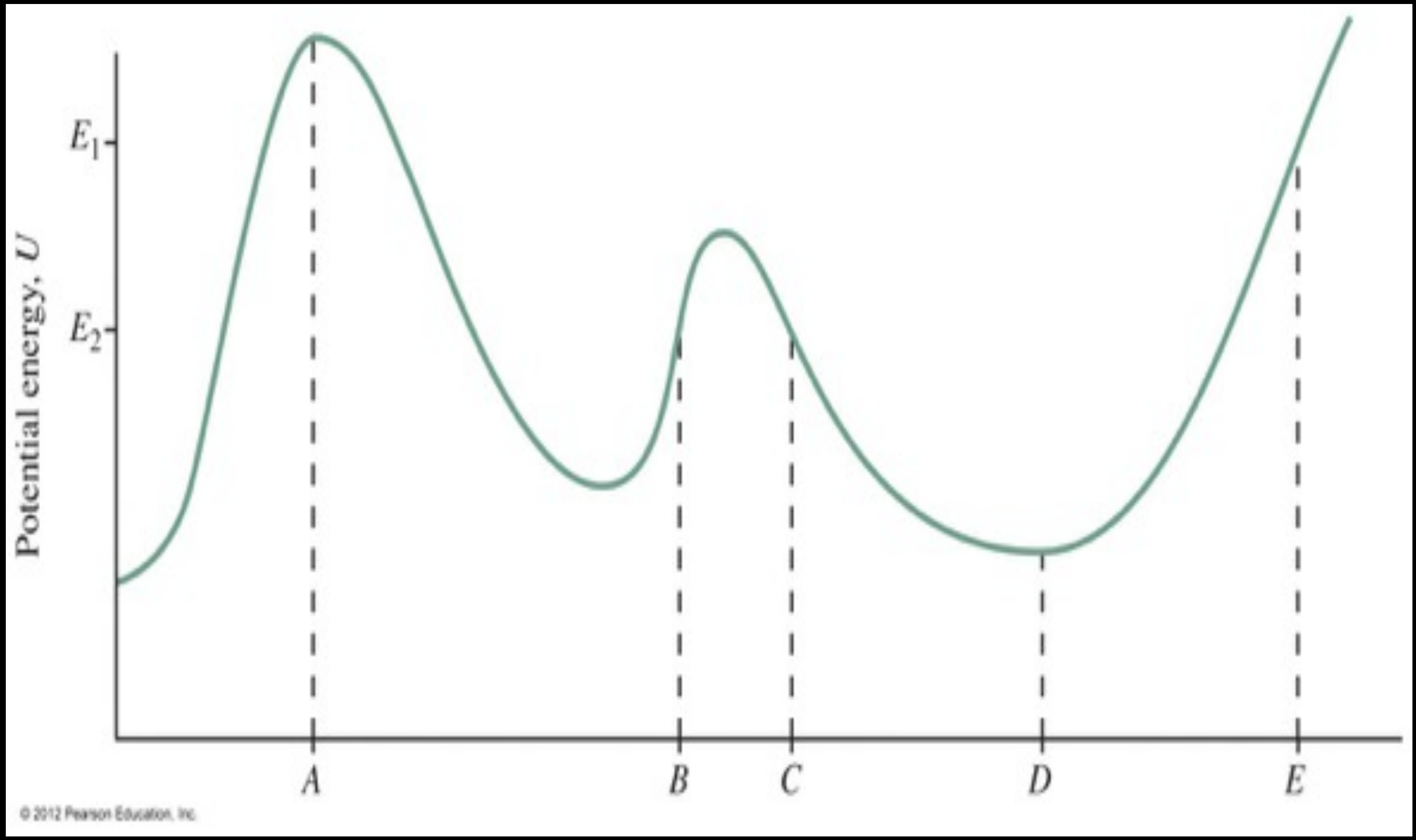
(d) D

(e) E

Force and potential energy

Quiz

Potential energy for an electron in a microelectronic device



Find the right-most point (one most right) where the force points to the left.

(a) A

(b) B

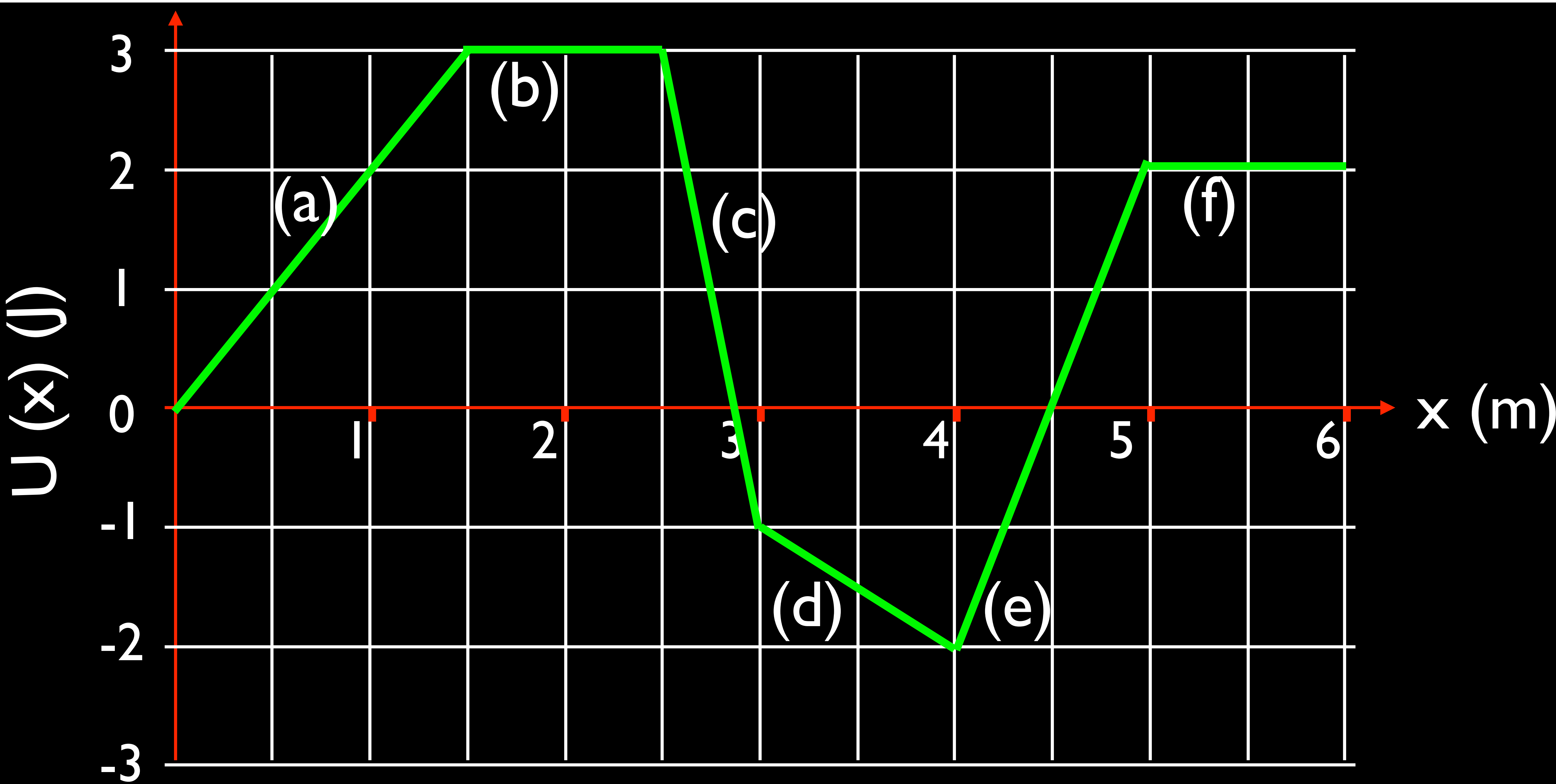
(c) C

(d) D

(e) E

Force and potential energy

Quiz

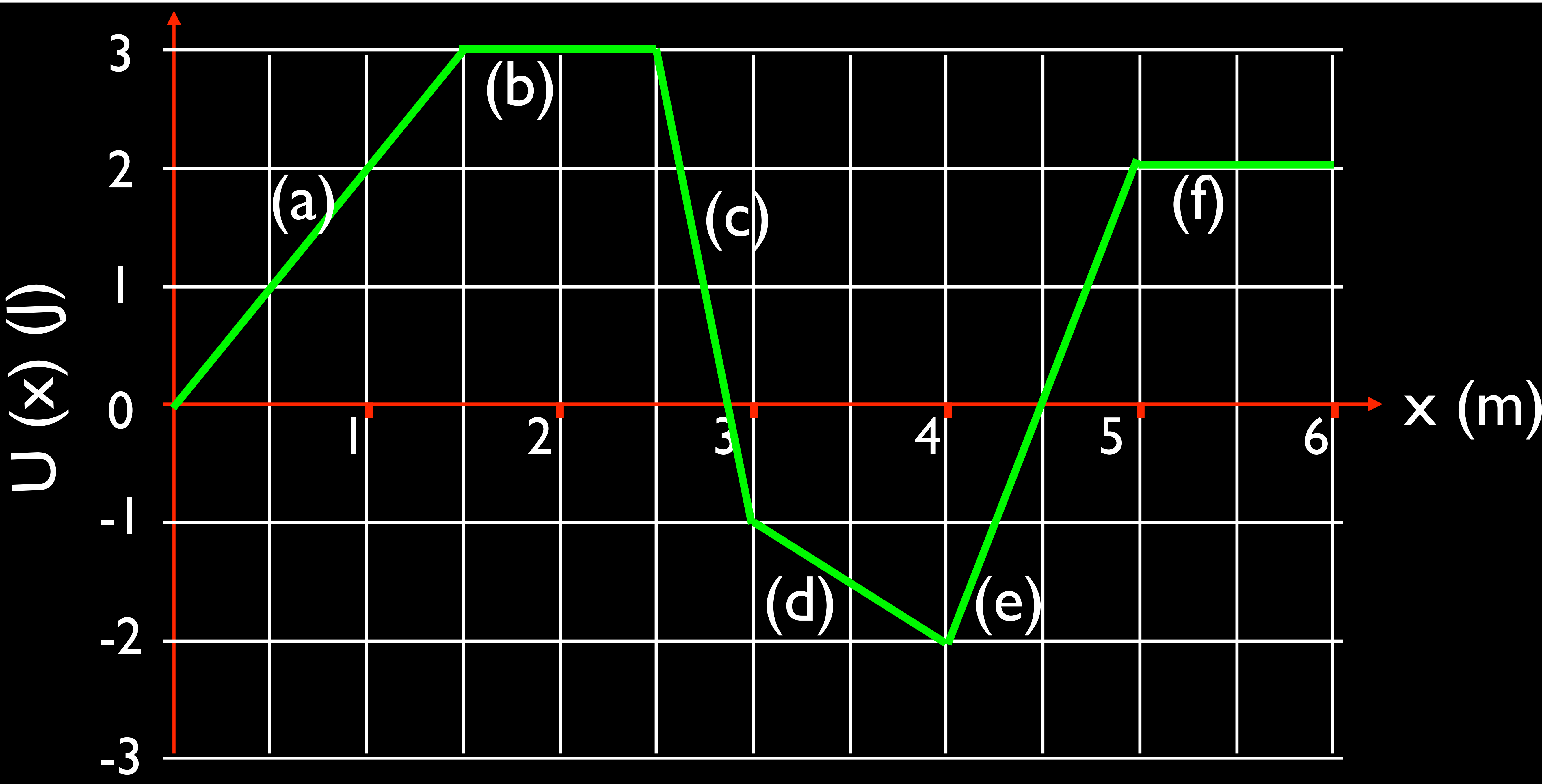


Force in segment (a)?

(a) -2N (b) 2N (c) 0.5N (d) -0.5N (d) 0 N

Force and potential energy

Quiz

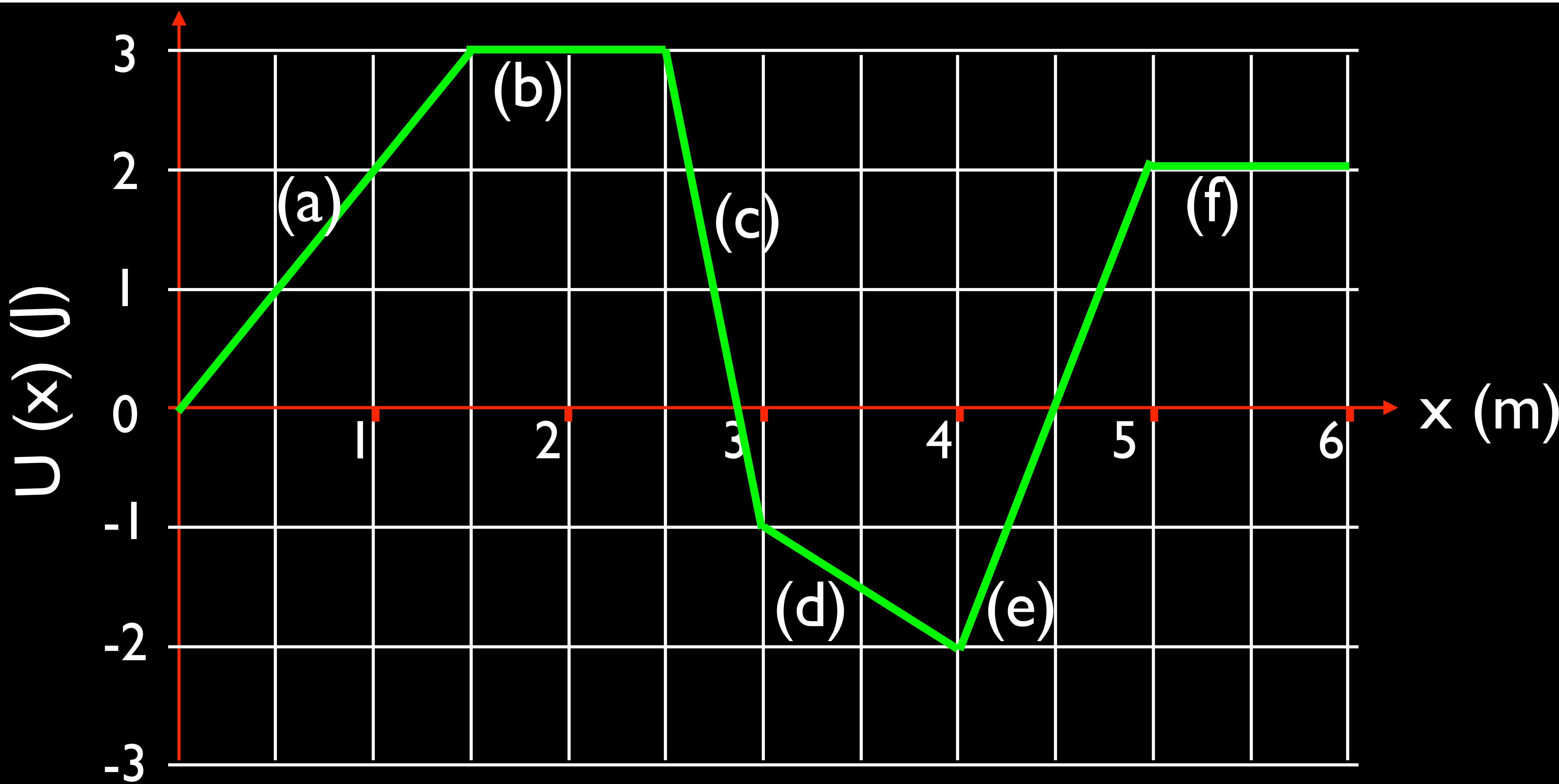


Force in segment (a)?

$$F(x) = -\frac{\Delta U}{\Delta x} = -\frac{3J}{1.5m} = -2N$$

Force and potential energy

Quiz

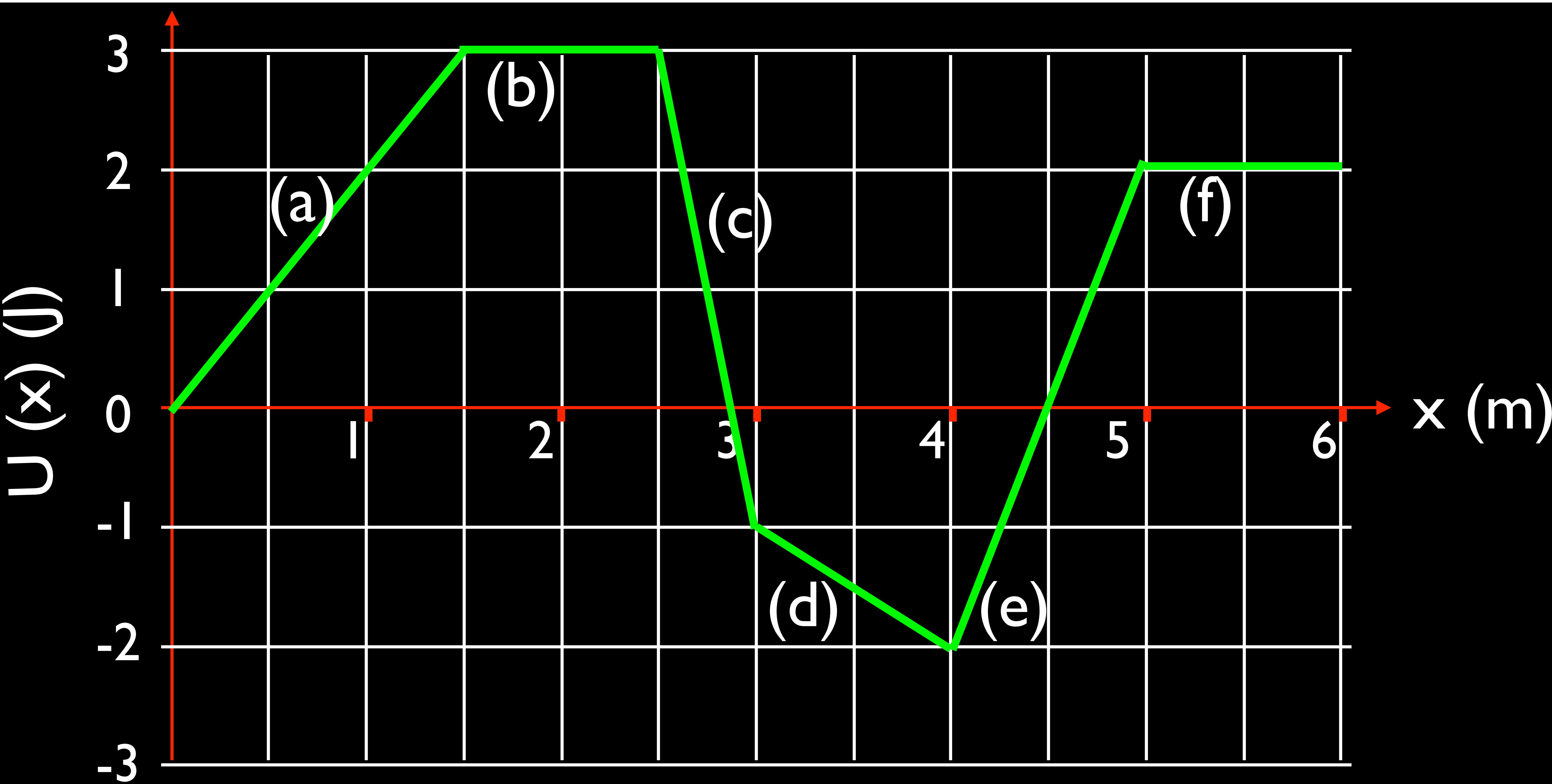


Force in segment (b)?

(a) -3N (b) 3N (c) 1.2N (d) -1.2N (d) 0 N

Force and potential energy

Quiz

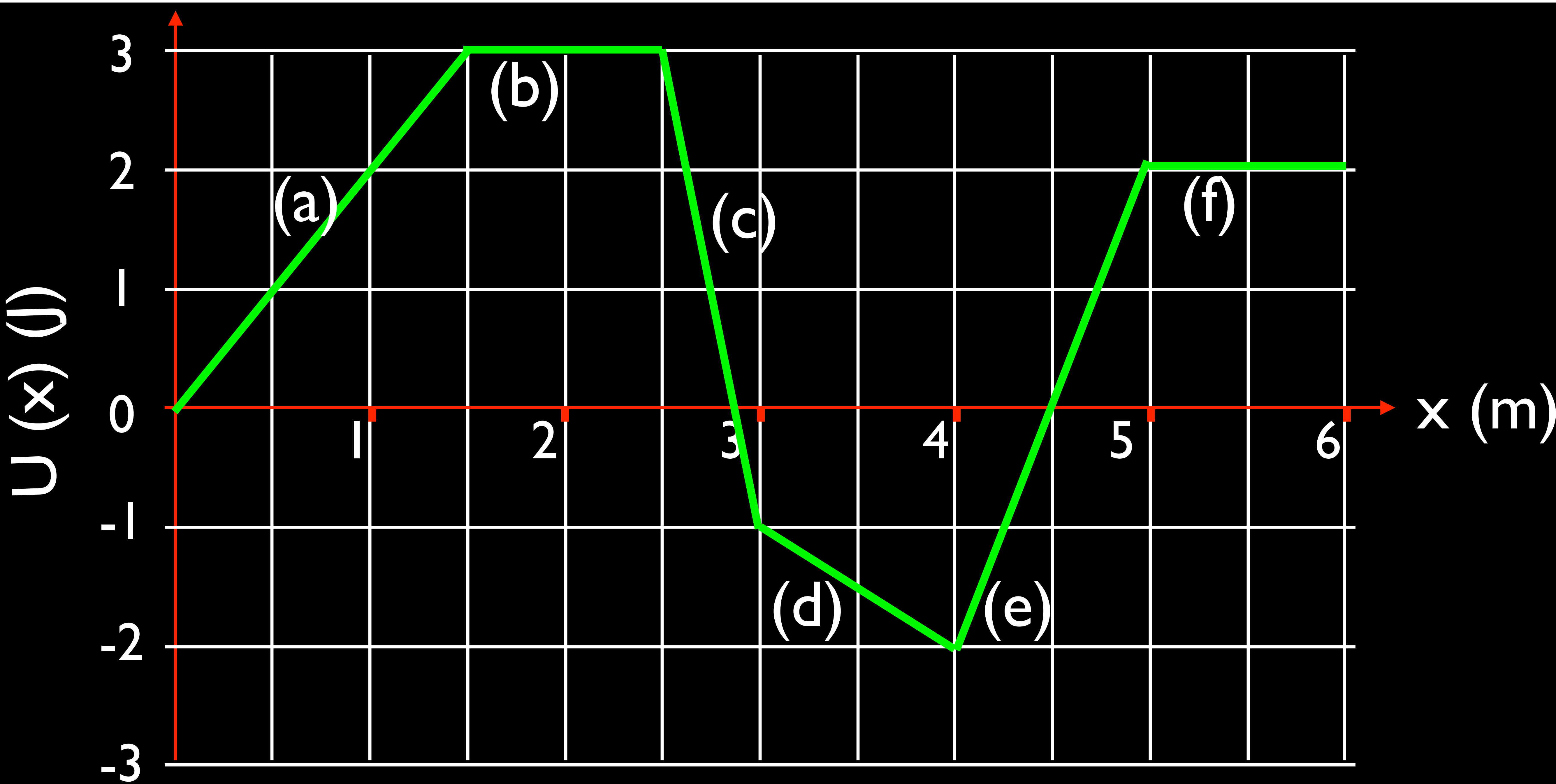


Force in segment (c)?

(a) -8N (b) 8N (c) -4N (d) 4N (d) 0 N

Force and potential energy

Quiz

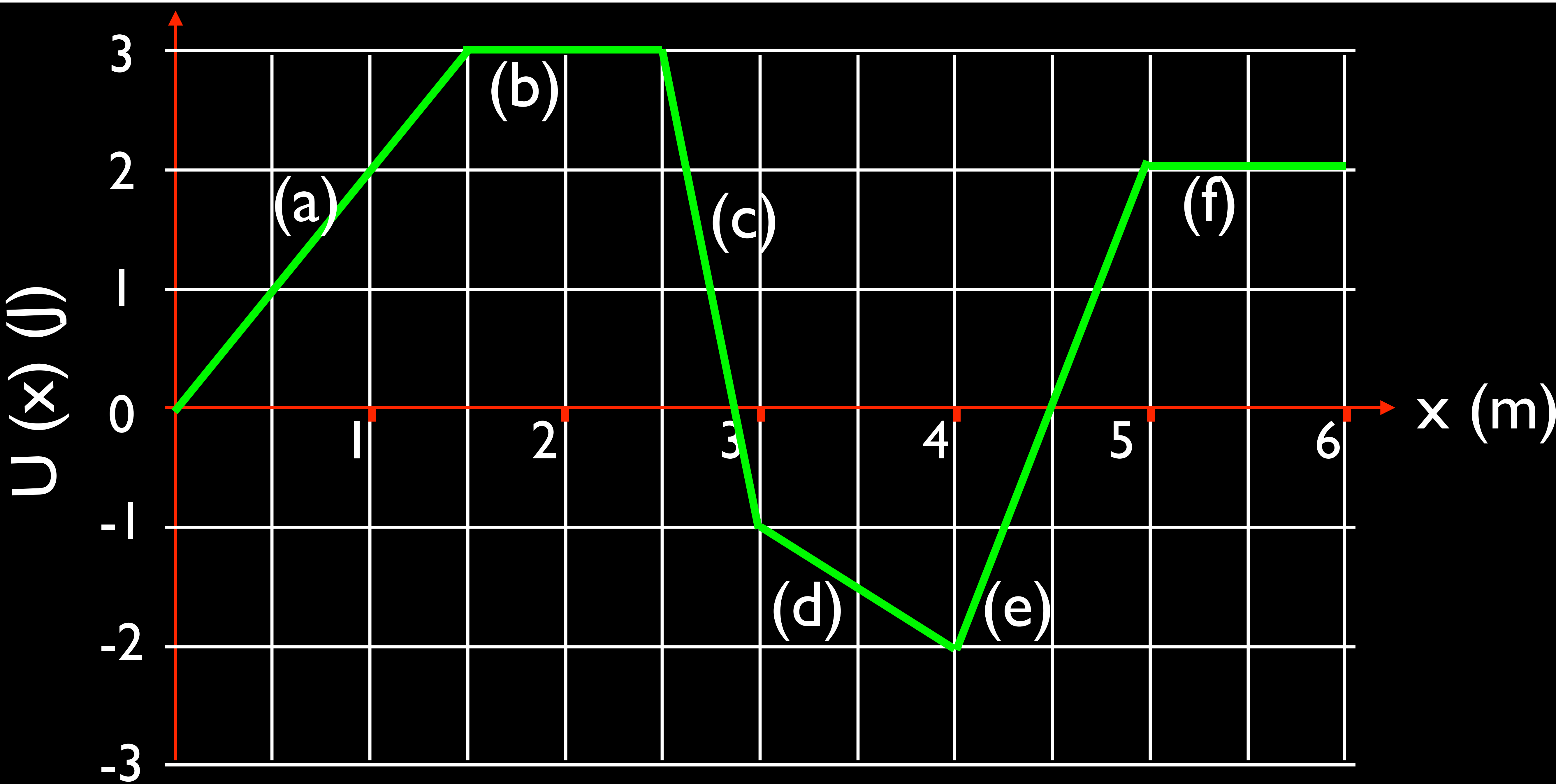


Force in segment (c)?

$$F(x) = -\frac{\Delta U}{\Delta x} = -\frac{-4J}{0.5m} = 8N$$

Force and potential energy

Quiz

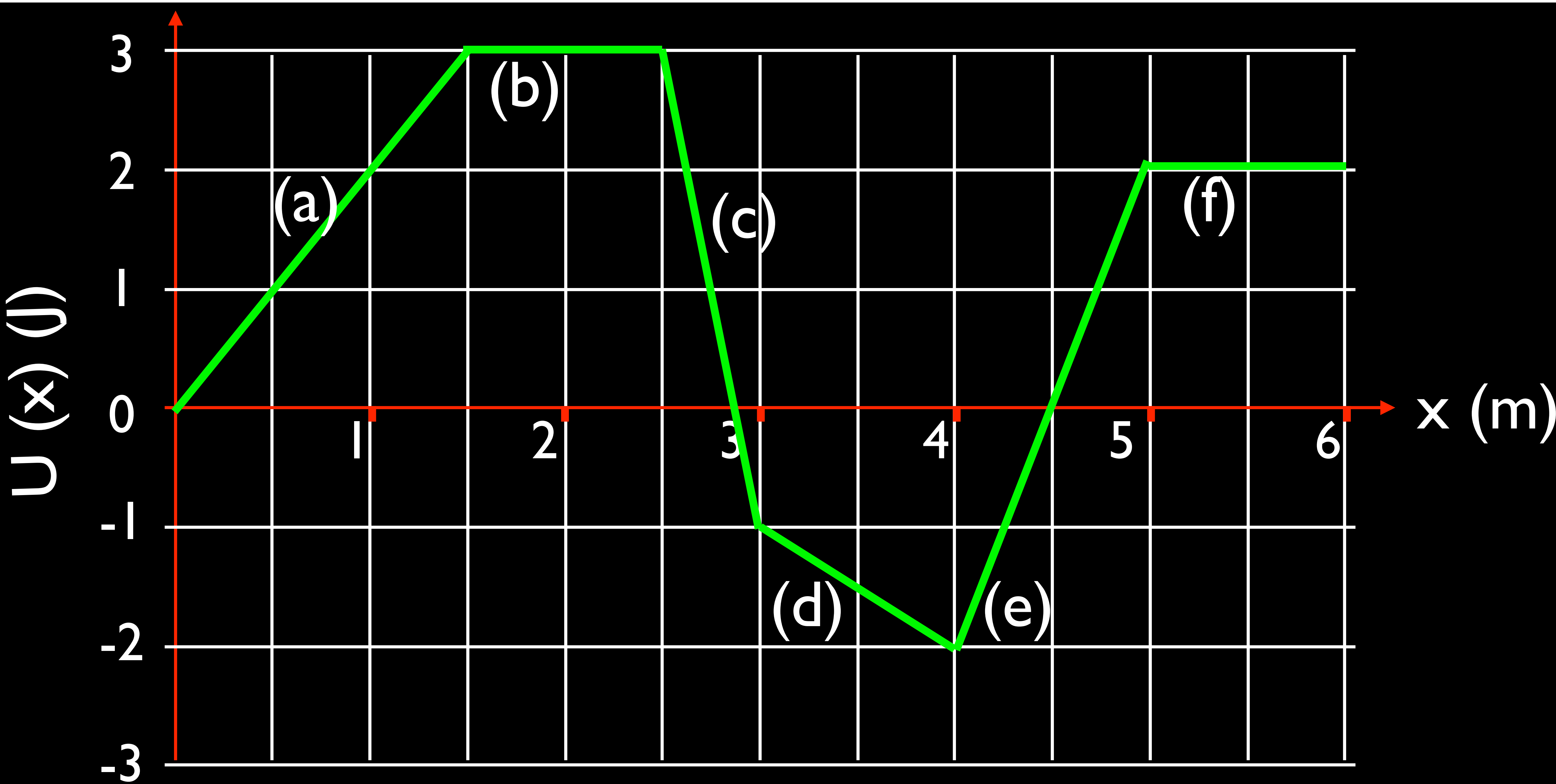


Force in segment (d)?

(a) -1N (b) 1N (c) -0.5N (d) 0.5N (d) 0 N

Force and potential energy

Quiz

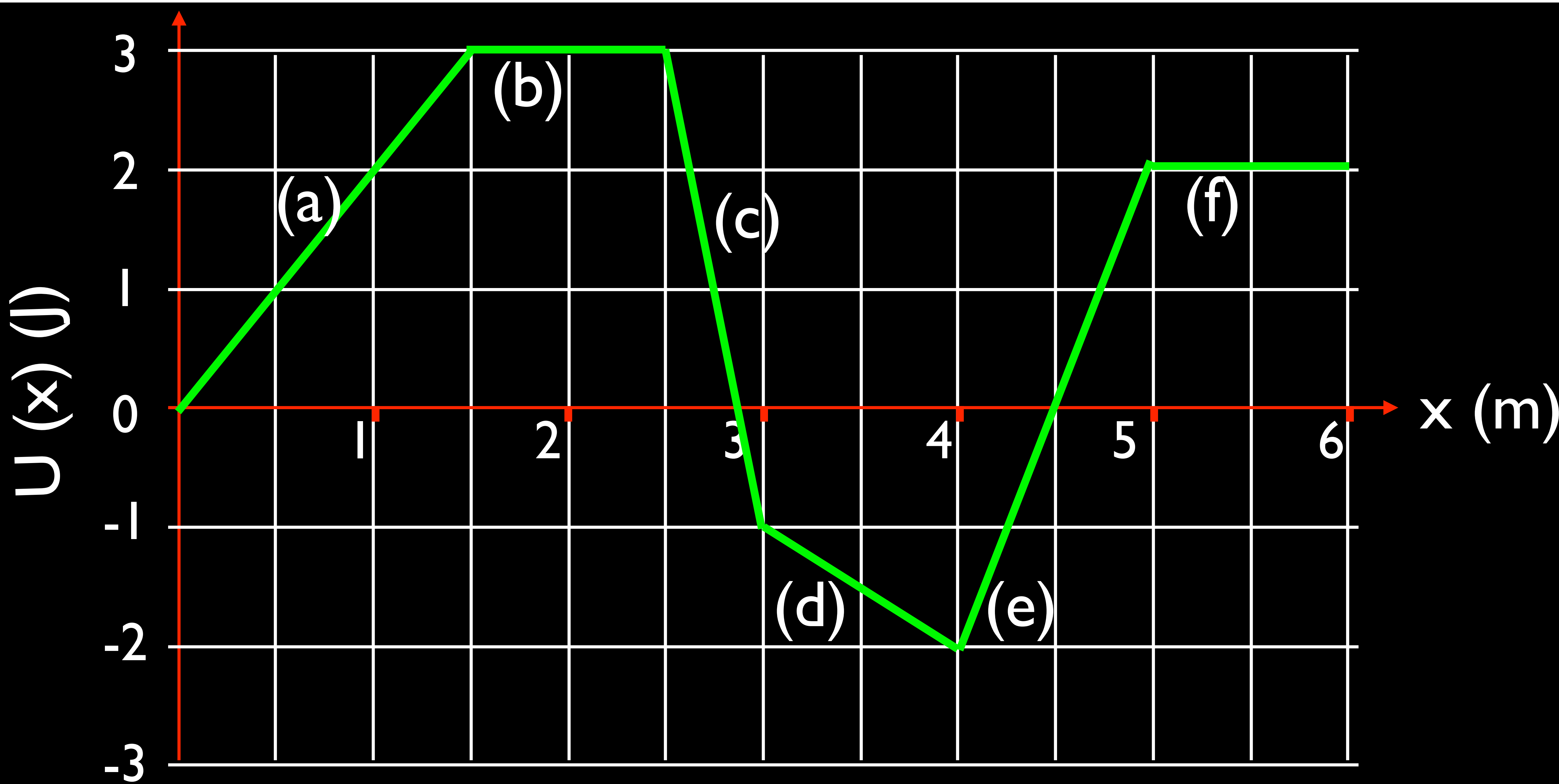


Force in segment (e)?

(a) -4N (b) 4N (c) -8N (d) 8N (d) 0 N

Force and potential energy

Quiz



Force in segment (f)?

(a) -2N (b) 2N (c) -1N (d) 1N (d) 0 N

Quiz

'Box 1' and 'Box 2' have the same mass, *m*.

They start at the top of 2 inclined planes at the same height.

The planes are inclined at 30° and 60°.

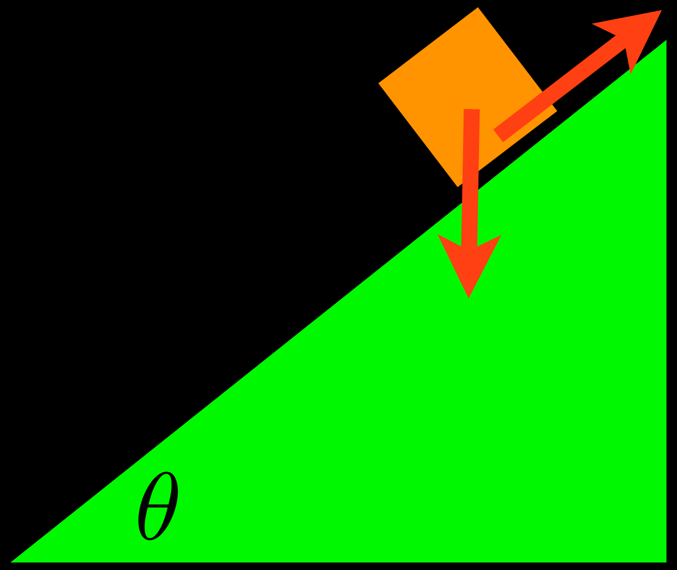
If the coefficient of friction, μ_K, is the same, which of the boxes is going faster when it reaches the bottom?

(a) Both blocks have the same speed

(b) Block 1 is faster

(c) Block 2 is faster

(d) We need to know more information



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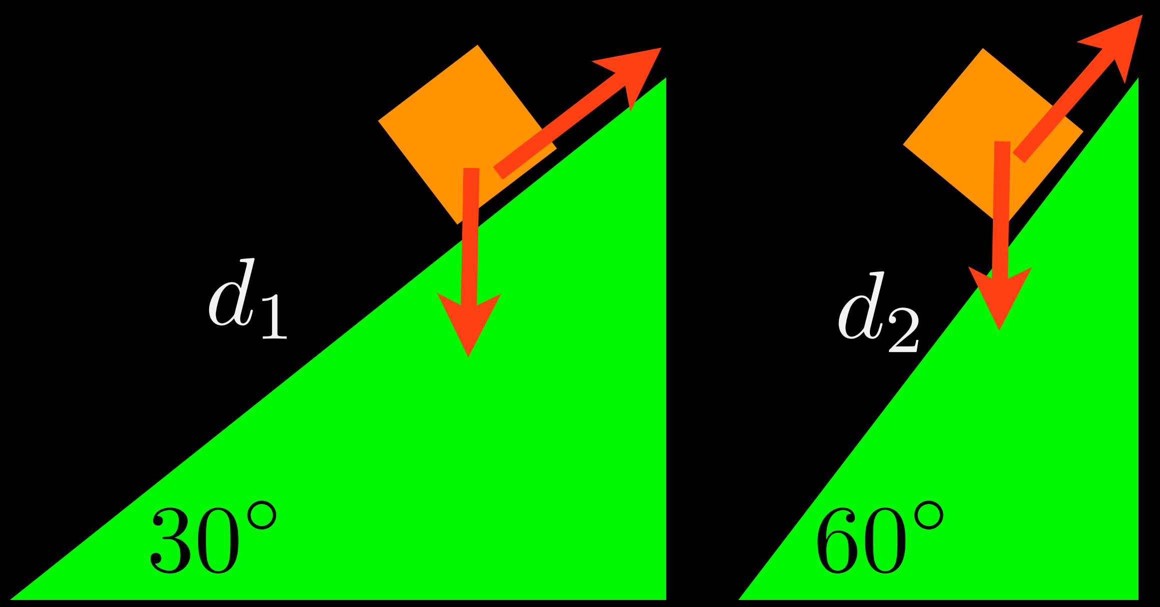
If the coefficient of friction, μ_K, is the same, which of the boxes is going faster when it reaches the bottom?

(a) Both blocks have the same speed

(b) Block 1 is faster

(c) Block 2 is faster

$d_1 > d_2$



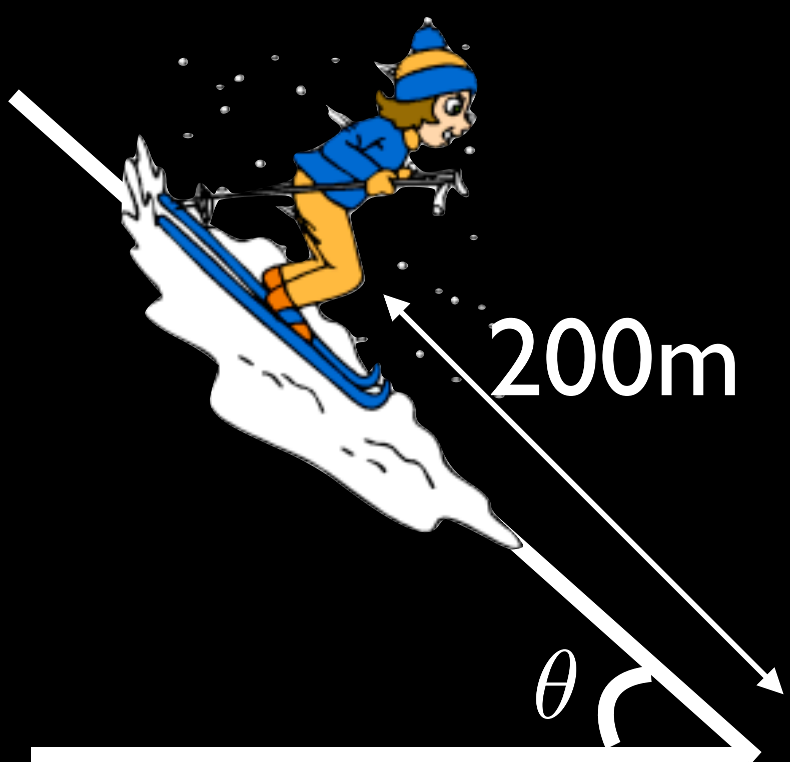
(d) We need to know more information

Quiz

A 50 kg skier starts from rest and travels 200m down a hill inclined at 20°.

When she reaches the bottom of the hill, her speed is 30 m/s.

How much work is done by friction as the skier comes down the hill?



(a) $-11,050\,\mathrm{J}$

(b) $-33,550\,\mathrm{J}$

(c) $-22,550\,\mathrm{J}$

(d) $-56,050\,\mathrm{J}$

Quiz

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(a) $-11,050\,\mathrm{J}$

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Quiz

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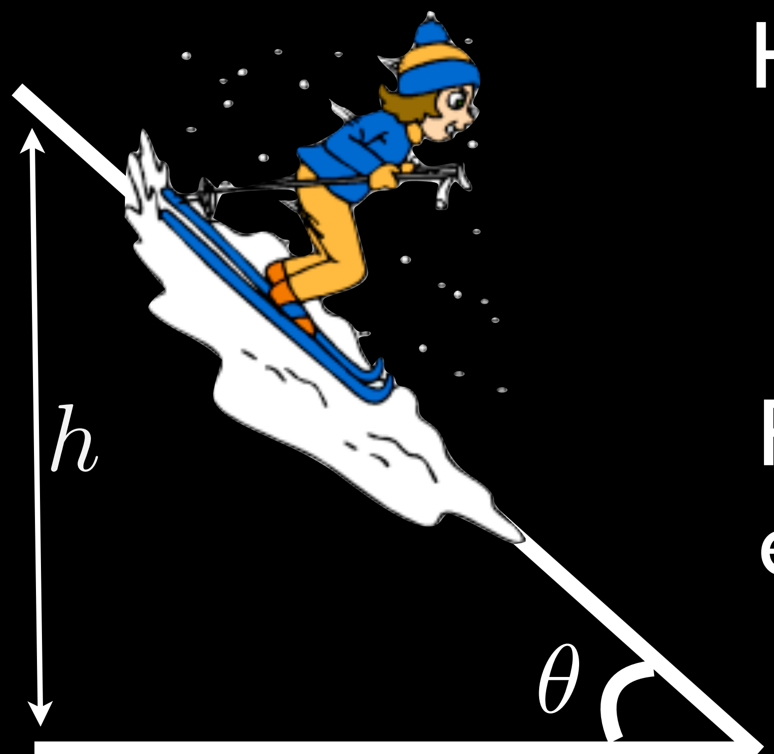
When she reaches the bottom of the hill, her speed is 30 m/s.

How much work is done by friction as the skier comes down the hill?

Energy: $E_{\text{tot}} = K - U - W_{\text{friction}} \quad = 0$



Height:

$$h = (200\,\text{m}) \sin 20^\circ$$
$$= 68.4\,\text{m}$$

Potential energy:

$$U = mgh$$
$$= (50\,\text{kg})(9.81\,\text{m/s}^2)(68.4\,\text{m})$$
$$= 33,550\,\text{J}$$

Quiz

A 50 kg skier starts from rest and travels 200m down a hill inclined at 20°.

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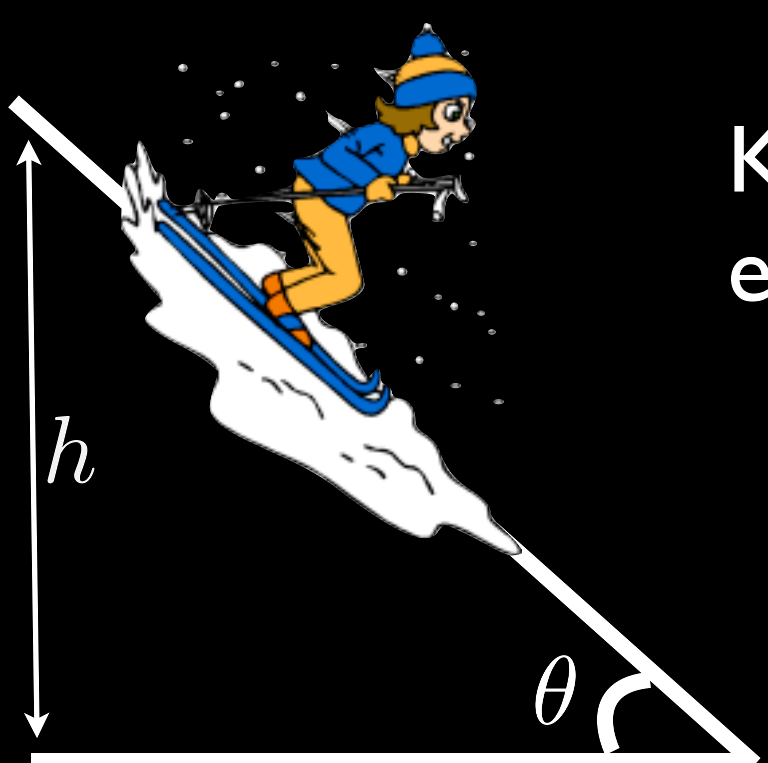


Kinetic energy:

$$K = \frac{1}{2}mv^2$$
$$= \frac{1}{2}(50\,\text{kg})(30\,\text{m/s})^2$$
$$= 22,500\,\text{J}$$

Quiz

A 50 kg skier starts from rest and travels 200m down a hill inclined at 20°.

When she reaches the bottom of the hill, her speed is 30 m/s.

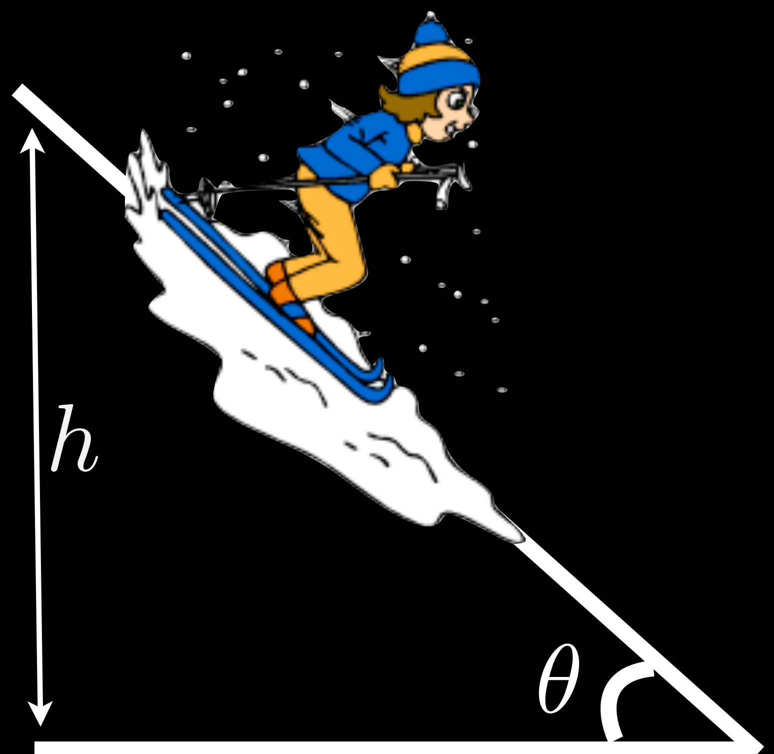
How much work is done by friction as the skier comes down the hill?

Energy: $E_{\text{tot}} = K - U - W_{\text{friction}} \quad = 0$

$$W_{\text{friction}} = K - U$$

$$= 22,500\,\text{J} - 33,550\,\text{J}$$

$$= -11,050\,\text{J}$$



Lecture 7 : Summary

- The difference between conservative and non-conservative forces
- Potential energy: what it is & how to calculate it
- Conservation of energy
- Potential energy curves