

CHAPTER - 3

PART 2 · ≈ 75 MIN

What Forces Act on the Selected System?

The free-body diagram is an engineering model, not a drawing procedure. Before a single force is drawn, decide what the system is — the diagram changes when the boundary changes.

Observe

›

Idealize

›

Model

›

Solve / Analyze

›

Validate

›

Report

2



A tow tractor pulling two loaded carts. Which forces matter depends entirely on where you draw the line.

AIRPORT TOW SYSTEM · SIDE VIEW



Airport apron scene, a small tow tractor pulling two loaded luggage carts in line. This is Chapter 3's recurring physical system. It returns in Part 3 for cause and effect, in Part 4 for the coupling, and in Part 7 to ask whether our answer was any good.



Nothing here is new physics

Weight, contact, friction, a coupling force. You met all of them in Statics. What is new is that the train is accelerating, so they no longer balance.



The question that organises Part 2

Not “what forces are there?” but “what forces cross the boundary I have chosen?” Those are different questions with different answers.

Observe

Idealize



Model



Solve / Analyze



Validate



Report



PREDICT

Draw your boundary around the whole train. Is the coupling force between the tractor and the first cart visible on your diagram?

Now draw it around the rear cart alone. What appears that was not there before?

Which of the forces you have drawn would still be there if the tractor were parked?



Three cuts, three diagrams. Sketch them before the reveal.

Observe



Idealize



Model



Solve / Analyze



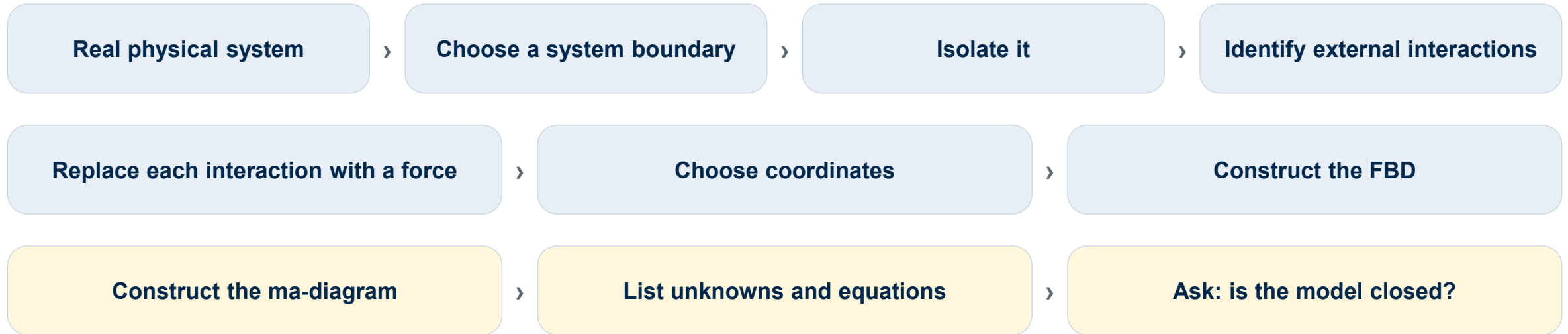
Validate



Report



Ten moves, in order. Nine of them happen before any force is drawn.



Where students usually start

At step 7 — drawing arrows on a picture. Everything that makes the diagram correct happened earlier.



Where Part 2 stops

At step 10. Part 2 never solves anything. Part 3 opens by solving the diagram Part 2 finished.

A free-body diagram is a set of claims about reality. Steps 1 to 4 decide which claims you are making.

Observe ›

Idealize ›

Model ›

Solve / Analyze ›

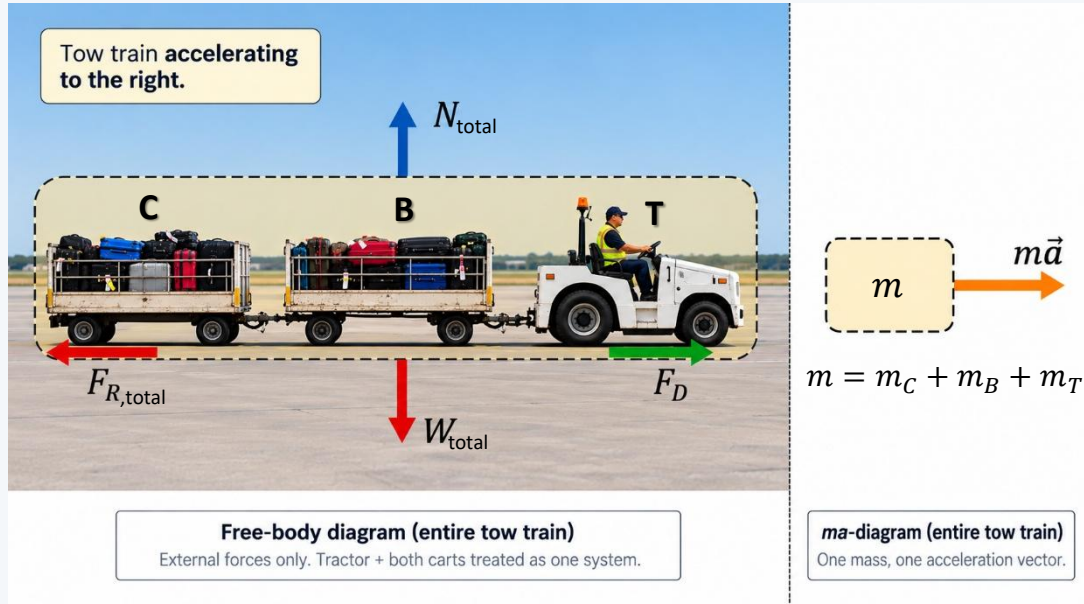
Validate ›

Report



One boundary around everything that moves together.

FBD + ma-DIAGRAM · WHOLE TRAIN



WHAT THIS CUT EXPOSES

Visible	the drive force at the road, the total weight, the total normal force
Hidden	the coupling force — it is internal to this system
Good for	finding the acceleration of the whole train
Useless for	sizing the hitch



Why this is legal

Part 1's system-of-particles result: internal forces cancel in pairs, so a system of bodies moving together obeys $\Sigma F = ma$ at its mass centre, with only external forces on the diagram.

Choosing a boundary is choosing which forces you are allowed to ask about.

Observe



Idealize

**Model**

Solve / Analyze



Validate

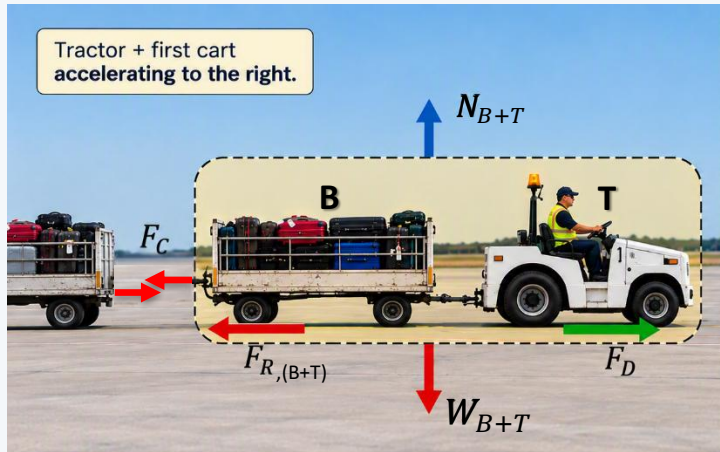


Report



Move the boundary one coupling to the rear and a force appears out of nowhere. It was always there.

FBD + ma-DIAGRAM · TRACTOR + CART B



Free-body diagram (tractor + first cart)
External forces only. The rear cart exerts a backward coupling force at the hitch.



$$m = m_B + m_T$$

ma-diagram (tractor + first cart)
One mass, one acceleration vector.

WHAT CHANGED

New force the rear coupling force, now external

Same as before weight, normal force, drive force, rolling resistance

Good for finding the load in the rear hitch

Note nothing physical changed — only the boundary



The force did not appear

It was acting the whole time. Cut 1 simply had it inside the system, where it cancelled against its own reaction.



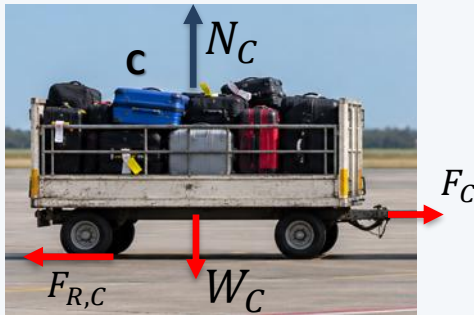
Newton's third law, in use

The rear cart pulls back on this system exactly as hard as this system pulls forward on the rear cart.



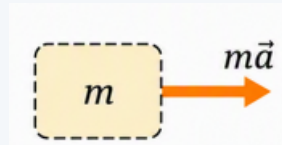
The smallest useful system, and the one that answers the engineering question.

FBD + ma-DIAGRAM · REAR CART



Free-body diagram

External forces only. Front cart B exerts forward coupling force



$$m = m_C$$

ma diagram (cart C only)

Only mass of cart C

THE SMALLEST USEFUL CUT

Visible	only the forces acting on this one cart
Hidden	everything about the tractor — and it does not matter
Good for	the coupling force, directly and in one equation
Design use	this is the number the hitch is sized from



The engineering habit

Cut where the unknown you want becomes external. If you need a connection force, put the boundary through the connection.

Same scene, three diagrams, three different questions answered. None of them is the “correct” diagram.

Observe



Idealize



Model



Solve / Analyze



Validate



Report



What each boundary exposes, what it hides, and what it is good for.

Boundary	Exposes	Hides	Use it when you want
Whole train	drive force, total weight and normal force	both coupling forces	the acceleration of the train
Tractor + front cart	the rear coupling force	the front coupling force	the load in the rear hitch
One cart alone	that cart's coupling force only	everything about the tractor	to size a single coupling



Unknown count changes with the cut

More boundaries means more diagrams, but also more equations. Part 4 makes that trade explicit.



A fourth cut is available

Put the boundary around the coupling itself. With no mass, its two end forces must be equal and opposite.

Observe



Idealize



Model



Solve / Analyze



Validate



Report



Each force on a diagram is a model. Say what it assumes.

WEIGHT

$$W = mg$$

Acts at the mass centre, always vertically downward. Assumes a uniform gravitational field over the body — excellent near the Earth's surface.

NORMAL FORCE

$$N \geq 0$$

Perpendicular to the contact surface. One-sided: a surface can push but never pull. $N = 0$ means contact has been lost — Part 5 builds on this.

CABLE TENSION

$$T \geq 0$$

Along the cable, pulling away from the body. Equal throughout only for a massless cord on a frictionless pulley — an assumption, not a fact.

THE RULE THAT APPLIES TO EVERY ENTRY

A force model is a claim about how the world behaves. Write the expression and the assumption together, every time. When a prediction later disagrees with a measurement, this list is the first place Part 7 will look.

Observe



Idealize

**Model**

Solve / Analyze



Validate



Report



Friction, springs and drag — the three that carry the most hidden assumptions.

FRICITION FORCE - F_f

F_f is the friction force. F_s is its static limit.
 F_k is its value during sliding.

$$F_f \leq F_s = \mu_s N$$

$$F_f = F_k = \mu_k N$$

The first is an inequality to be tested; the second is an equation to be used. Which applies depends on whether sliding is happening.

LINEAR SPRING FORCE – F_s

$$F_{spr} = k s$$

s is the deformation from the unstretched length — not the length. Assumes a massless spring, linear over the range used, and no yielding.

FLUID DRAG

$$F_D = c v_{sp}^2$$

Opposes motion relative to the fluid. The square law holds only in a speed regime; at low speed a linear law fits better. Part 3 uses this one hard.



Friction is the one students get wrong, and it is worth saying plainly

Friction opposes relative sliding at the contact — not the motion of the body. A box riding on an accelerating truck bed is moving, is not sliding, and is held by static friction pointing forward.

None of these three forces gets a section of its own. They appear wherever the system needs them.

Observe



Idealize

**Model**

Solve / Analyze



Validate



Report

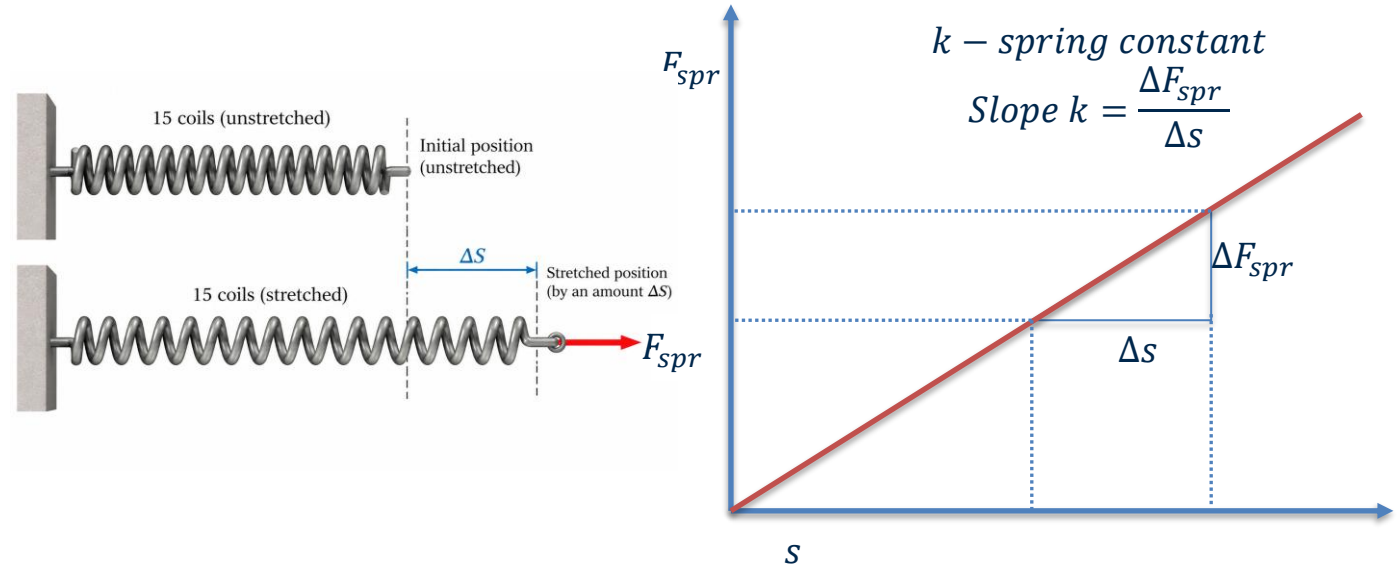


Spring force:

LINEAR SPRING

$$F_{spr} = k s$$

s is the deformation from the unstretched length — not the length. Assumes a massless spring, linear over the range used, and no yielding.



Friction exists between two surfaces

Friction opposes relative sliding at the contact — not the motion of the body.

None of these three forces gets a section of its own. They appear wherever the system needs them.

Observe



Idealize

**Model**

Solve / Analyze



Validate



Report



Friction force:

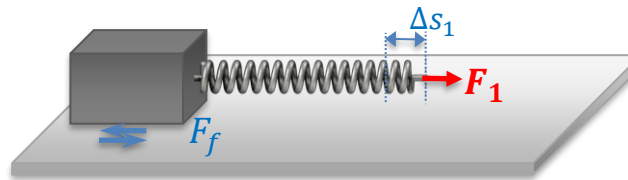
FRICITION

F_f actual friction force

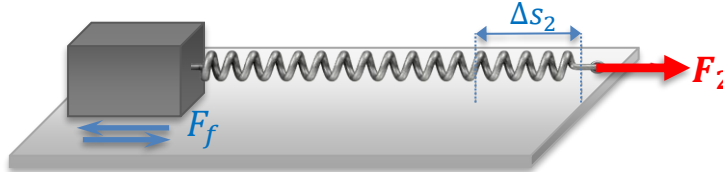
$F_s = \mu_s N$ maximum limit of static force

$F_k = \mu_k N$ kinetic force magnitude

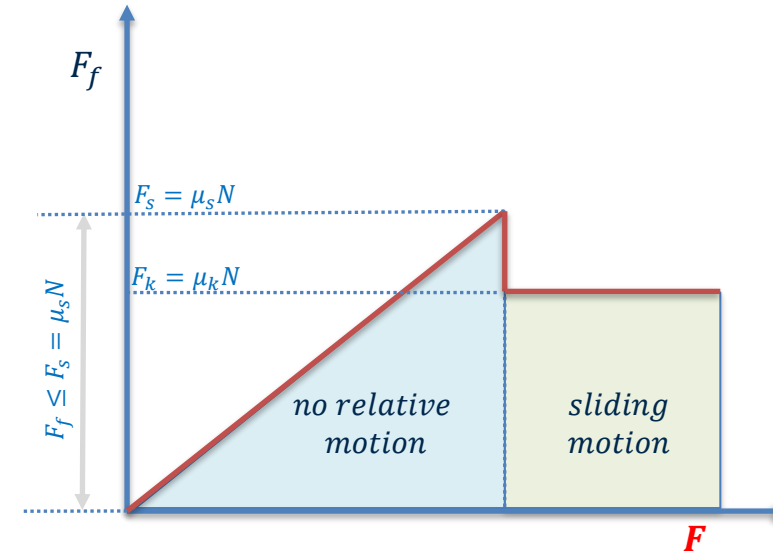
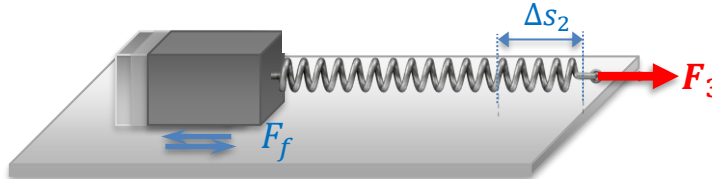
$F_s = \mu_s N > F_f = \mathbf{F_1}$ No relative motion



$F_s = \mu_s N = F_f = \mathbf{F_2}$ Impending motion



$F_k = \mu_k N = F_f = \mathbf{F_3}$ Motion-Sliding



Friction is a contact force between two surfaces.

The friction forces on the two surfaces form an equal-and-opposite action–reaction pair.

Friction opposes relative sliding at the contact — not the motion of the body.

None of these three forces gets a section of its own. They appear wherever the system needs them.

Observe



Idealize



Model



Solve / Analyze



Validate



Report



The free-body diagram holds forces. The ma-diagram holds the consequence.

FREE-BODY DIAGRAM

Every external force acting on the isolated body, drawn where it acts, with a source you can name: a surface, a cable, the Earth, the air.

- if you cannot name what applies it, it is not a force
- ma never appears here
- reactions to these forces act on other bodies, not on this one

ma-DIAGRAM

The same body, drawn again, carrying the vector $m \vec{a}$ — the mass-acceleration representation. It is the right-hand side of the equation, not another force.

$$\sum \vec{F} = m \vec{a}$$

left diagram = right diagram



Nomenclature decision for this course

The right-hand diagram is called the ma-diagram. The phrase “inertial force” is retired: it names ma as though it were a force, which is exactly the misconception the second diagram exists to prevent.

Observe



Idealize

**Model**

Solve / Analyze



Validate

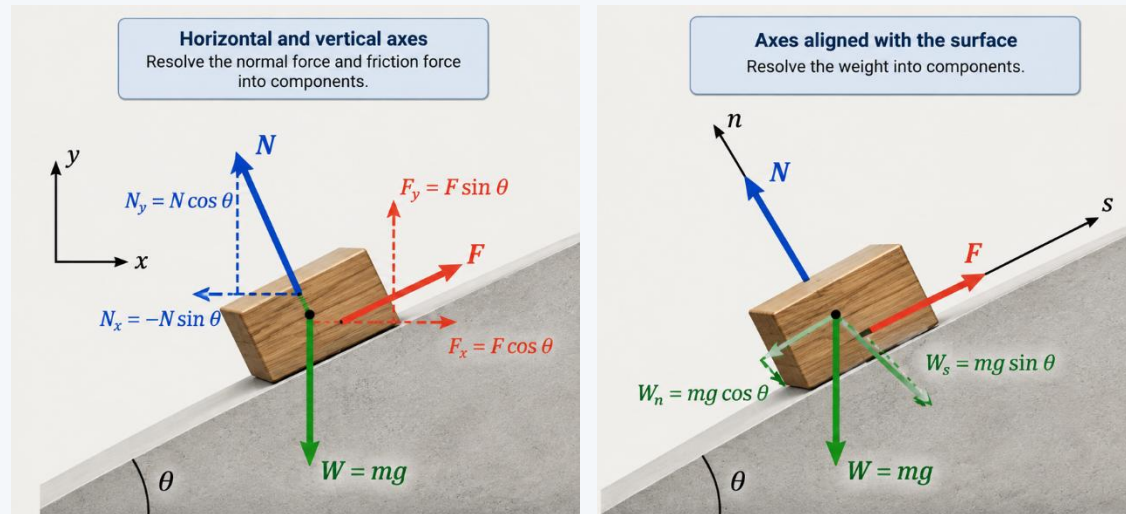


Report



The same body, the same forces, two axis choices — and very different algebra.

ONE INCLINE, TWO FRAMES



HORIZONTAL / VERTICAL AXES

Two unknown force components and two acceleration components. The normal force and the friction force each need resolving.

AXES ALONG THE SURFACE

The acceleration has one component. Only the weight needs resolving. Fewer unknowns, same physics, less to get wrong.



The principle, stated once

Choose the frame that makes the acceleration simple, not the one that makes the forces simple. The acceleration is what the equation is about.

And whichever you choose, keep the same positive directions when the kinematics arrives in Part 3.

Observe



Idealize

**Model**

Solve / Analyze



Validate



Report



Count the unknowns, count the equations you actually have, and name what is missing.

FOR THE REAR CART, CUT 3

Unknowns	the coupling force, the normal force, the acceleration — three
Equations	two component equations from $\Sigma F = m a$
Force laws	rolling resistance modelled as a fraction of N — one more
Verdict	three and three. Closed.

AND WHEN IT IS NOT CLOSED

Put two carts on one hitch and the count runs short by exactly one. No amount of extra force equations will fix it, because the missing information is not about forces at all — it is about how the connection restricts the motion.

That is Part 4, and the deficiency is worth feeling now.



No universal formula is offered here

Count each system on its own. A memorised equation-counting rule stops students from looking at the system, which is the one thing this Part is trying to teach.

You can tell whether a problem is solvable before you solve it. That is a professional habit, not a trick.

Observe



Idealize

**Model**

Solve / Analyze



Validate



Report



Does it slip? That is a decision, not a formula — and the pattern transfers everywhere.

CRATE ON A TRUCK BED



1

Assume it does not slip

Then the crate has the same acceleration as the truck.

2

Find the friction required

Whatever horizontal force the crate needs to accelerate with the bed.

3

Compare with the limit

Is the required friction less than or equal to $\mu_s N$?

4

Accept or reject

If it exceeds the limit, the assumption was wrong: the crate slides and μ_k applies instead.



No arithmetic in Part 2 — that is deliberate

The logic is the content. Part 3 runs the same four steps with numbers in them, once the equations are available.

Assume, compute the requirement, compare against the limit, accept or reject. You will use this again in Part 5.

Observe



Idealize



Model



Solve / Analyze



Validate

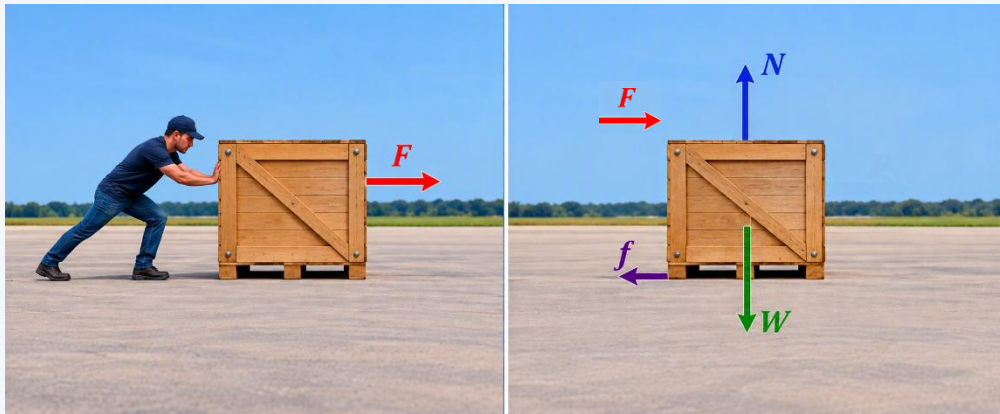


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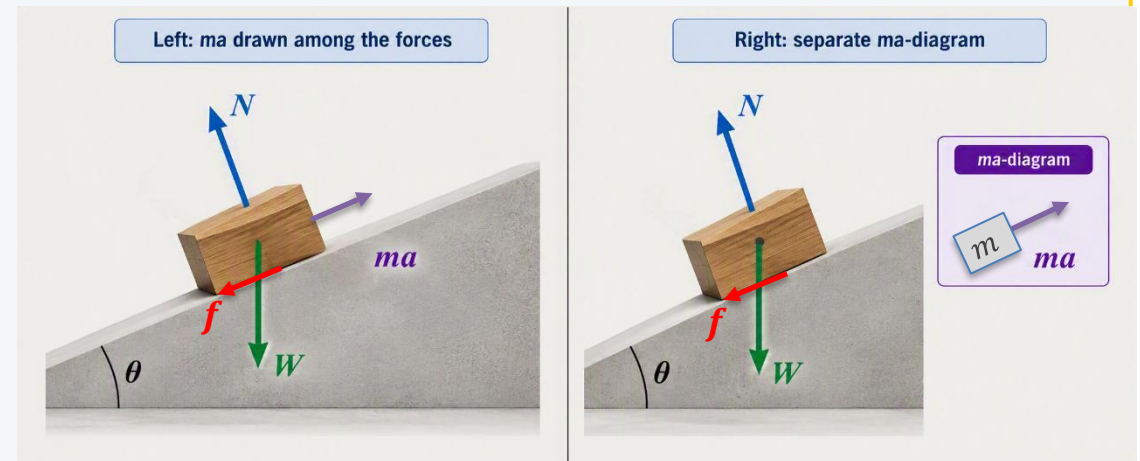


Two pairs. Each bad diagram has exactly one named defect.

PAIR 1 · A FORCE WITH NO SOURCE



PAIR 2 · ma DRAWN AS A FORCE



Defect 1 — a force with no source

Ask what applies it. “Motion” is not an answer; nothing in the surroundings is doing it.



Defect 2 — ma on the FBD

It belongs on the right-hand diagram. Drawing it among the forces turns an equation into a contradiction.

Observe



Idealize



Model



Solve / Analyze



Validate

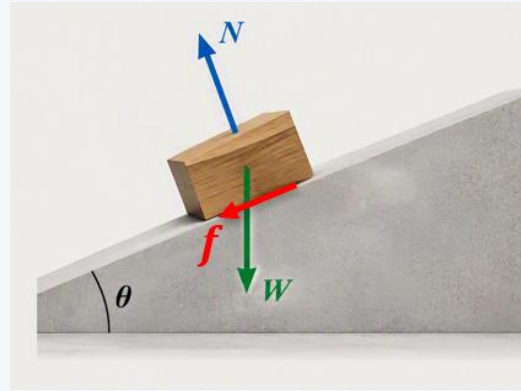
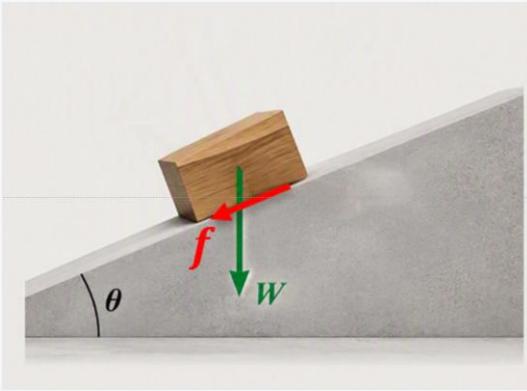


Report



Two more. One is a missing force; one is a force pointing the wrong way.

PAIR 3 · A MISSING NORMAL FORCE



PAIR 4 · FRICTION OPPOSING THE WRONG THING



Defect 3 — an omission

The surface is in contact and is being pressed on, so it must be pushing back. Omissions are harder to see than errors.



Defect 4 — the wrong relative motion

Friction opposes sliding at the contact. There is no sliding here, so it is static, and it points forward.

Observe



Idealize



Model



Solve / Analyze



Validate



Report



The narrow task AI does well, and the case where it does not.

ACTIVITY C2

1. Photograph your own free-body diagram for the rear cart.
2. Ask an AI what is missing or wrong with it.
3. Judge the critique. Which points are physically correct, which are style, and which are simply wrong?
4. Write one sentence: what did the critique catch that you would not have?



Where it is genuinely strong

Checking completeness against a checklist — a missing normal force, an unlabelled arrow, a missing coordinate frame.



Where it is not

Judging whether the boundary you chose was the useful one. That is an engineering decision about your purpose, and the AI does not know your purpose.



MEASURE · make tension a measured quantity

A spring scale in line with a cord pulling a loaded box: the reading changes between start-up and steady pull.

Two of the supplied diagrams have defects that a typical AI critique misses. Finding those is the point of the exercise.

Observe



Idealize



Model



Solve / Analyze



Validate



Report



Validate the model, not an answer — there is no answer yet.

What the diagram says	What must be true of the real system
a single weight vector at one point	the body is small enough, or uniform enough, to treat as a particle
one normal force	contact happens over a region small enough to replace by one resultant
rolling resistance as a backward force	the wheels turn freely and the bearings are not seizing
the coupling force along the drawbar	the hitch is a two-force member and carries no moment



Every row is a claim Part 7 is allowed to challenge

When the measured acceleration disagrees with the predicted one, this is the list you return to. Keep it with the diagram.

A model you cannot state the assumptions of is a model you cannot defend — or improve.

Observe



Idealize



Model



Solve / Analyze



Validate



Report



Each is either a true statement, or a true statement with its condition removed.

1

“Friction always opposes motion.”

It opposes relative sliding at the contact. A box that is not sliding on an accelerating truck bed is the counterexample.

2

“ $N = mg$.”

Only on a level surface, with no vertical acceleration and no other vertical force. Part 1's elevator already broke it.

3

“The spring force is k times the length.”

It is k times the deformation from the unstretched length. The difference is the entire content of the model.

4

“Tension is the same everywhere in the cord.”

True for a massless cord running over a frictionless pulley. That is an assumption you are making, and Part 4 leans on it heavily — so it is worth saying out loud.

5

“The coupling force appears when you cut there.”

The force was acting all along. Cutting elsewhere merely put it inside the system, where it cancelled against its own reaction pair.

Observe



Idealize



Model



Solve / Analyze

**Validate**

Report



Part 2 — the free-body diagram as an engineering model



You can now EXPLAIN

- why the same scene produces different diagrams
- what each force model assumes, and when it fails
- why friction can point in the direction of motion
- why ma is never drawn among the forces
- what it means for a model to be closed



You can now DO

- choose a boundary that exposes the unknown you want
- draw a complete FBD and a separate ma -diagram
- write each force from its model, with the assumption stated
- choose axes that make the acceleration simple
- run the slip test as a decision, and say which branch you took

Next — Part 3: the diagram is complete and the unknowns are counted. Nothing has been solved — and the reason to solve it is that the net force on this cart is what is making it speed up.

Observe



Idealize



Model



Solve / Analyze



Validate



Report