

Part IV — Control

Sense, Compare, Correct

Online, with a lab for each exercise: thinking-in-diagrams.aryehnielsen.com

Feedback control diagrams

Part IV · Control · Chapter 8 of 12 · the first of two chapters on feedback control diagrams

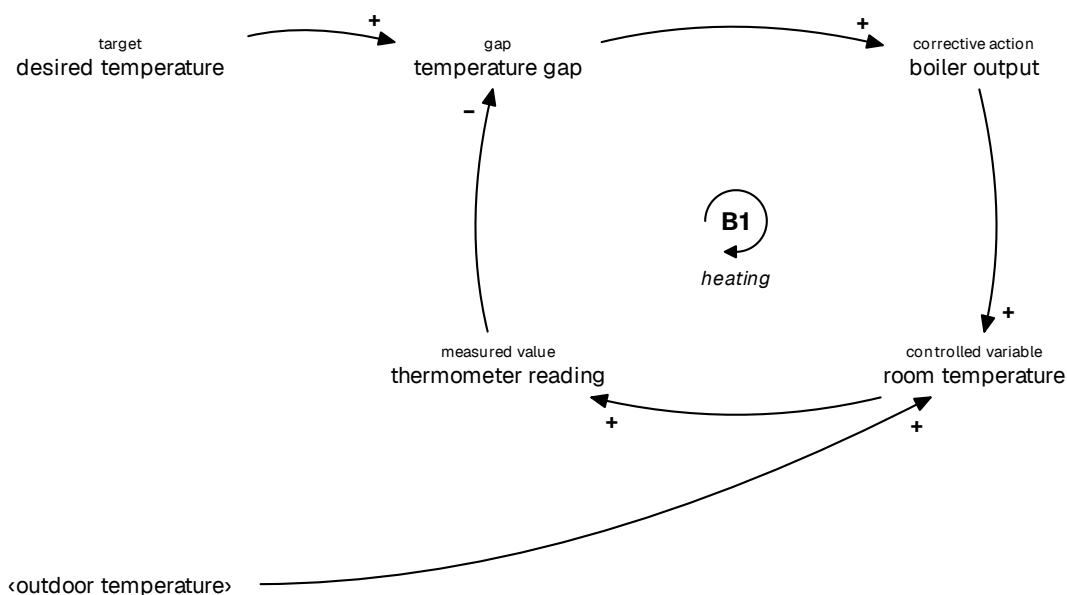
How does anything stay near a target? Its value is read, the reading is compared with the target, and the difference is corrected, in a loop. In a feedback control diagram, the part each variable plays in that loop is written above its name.

Signals you need this diagram

- Someone has chosen a value for a quantity to stay near: a temperature, a speed, a rate of inflation.
- The quantity and the reading of it can disagree, or the reading arrives late.
- A correction overshoots, or goes on after the quantity is back where it was wanted.
- Something outside keeps pushing the quantity away from that value.

A house kept warm on a winter evening

It is -2°C outside, and someone sets the thermostat's dial to 20°C . While the thermostat's thermometer reads less than 20°C , the boiler runs and the room warms. At 20°C the boiler stops, the room loses heat to the cold outside, the reading falls, and the boiler starts again.



What the notation expresses

A **feedback control diagram** is drawn as a causal loop diagram is, with the part each variable plays written in small type above its name, one part per variable. Its effects are **signals**: they carry readings and settings, not material.

Target and gap

The **target** is the value someone chooses for a quantity to stay near: *desired temperature*, 20 °C. No signal ends at a target, and a change of target is a new choice, not an effect.

The **gap** is chapter 4's gap thinking-in-diagrams.aryehnielsen.com/feedback/loops-that-amplify-loops-that-correct/#the-gap: the difference between the target and the measured value. The target's and the measured value's signals into it carry opposite polarities: *desired temperature* → *temperature gap* is +, *thermometer reading* → *temperature gap* is −. Only the measured value's signal lies on the loop, so it is the one the parity rule

thinking-in-diagrams.aryehnielsen.com/feedback/loops-that-amplify-loops-that-correct/#the-parity-rule counts.

Measured value

The **measured value** is the controlled variable as it is read: *thermometer reading*, a variable of its own, with a signal from *room temperature*. The two come apart: a thermometer above a radiator reads the radiator's heat, not the room's.

CHECK YOUR UNDERSTANDING

A kitchen fridge's thermostat reads the air by the door. Each time the door opens, warm kitchen air reaches the thermostat first and the compressor starts, while the food at the back stays cold; by evening the milk on the back shelf has frozen. In a feedback control diagram of the fridge, which variable is the measured value?

- a the temperature of the food on the back shelf
- b the thermostat's reading of the air by the door
- c the setting on the dial

Feedback: Answers, chapter 8

Corrective action

The **corrective action** is the variable changed to close the gap: *boiler output*, in kilowatts. The boiler is a thing; its output is a quantity, and only quantities are drawn. *Temperature gap* → *boiler output* is +: the wider the gap, the more heat the boiler puts out.

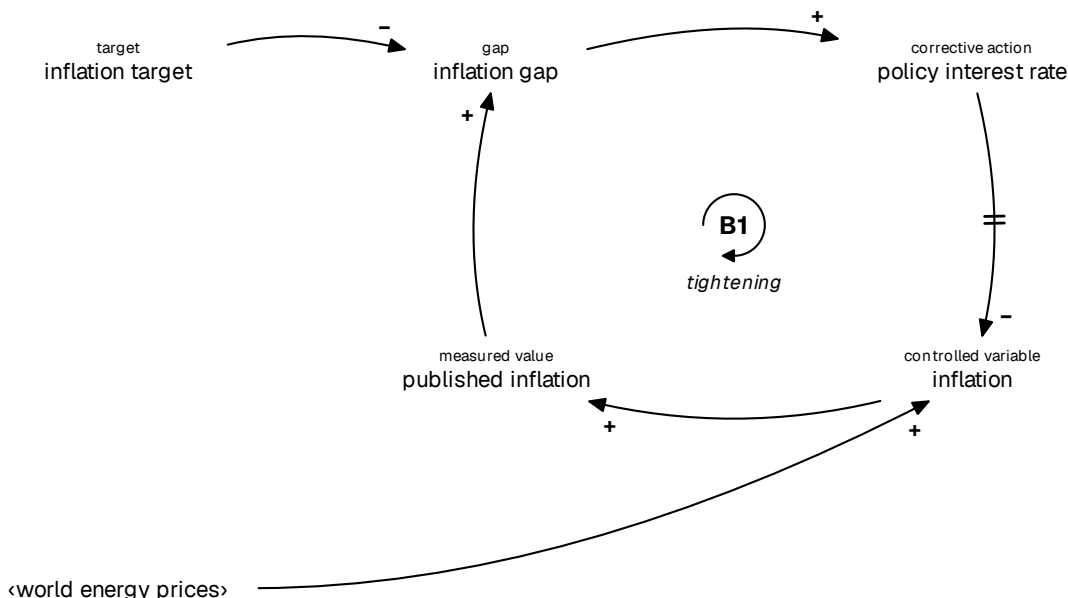
Controlled variable

The **controlled variable** is the quantity the corrective action holds near the target: *room temperature*. The measured value reads it. The target and the measured value are counted in its units, degrees.

Control loops

A **control loop** is a declared balancing loop that runs from a gap through a corrective action, a controlled variable and a measured value, back to the gap: B1 *heating*, from *temperature gap* through *boiler output*, *room temperature* and *thermometer reading*.

A central bank steering inflation is drawn with the same six variables, roles and signals. The government sets the Bank of England a target of 2% inflation, and the Bank raises its policy interest rate, Bank Rate, to bring inflation down.



Here the gap is inflation *above* the target, so the target's signal into it is – and published inflation's +; a higher rate lowers inflation, –. The loop holds one – signal, as the thermostat's does.

External drivers

In a feedback control diagram, an external driver

thinking-in-diagrams.aryehnielsen.com/feedback/delays-drivers-and-competing-loops/#external-drivers acts on the controlled variable: *outdoor temperature* → *room temperature*, +. It may also act on the measured value, as noise, a draft across the thermometer, or on the corrective action, a path chapter 9 draws. It never acts on a gap or a target.

World energy prices act on inflation: the Bank of England names Russia's invasion of Ukraine, which cut the supply of gas and raised its price, among the causes of the rise in inflation. Like any external driver, they lie outside the boundary thinking-in-diagrams.aryehnielsen.com/feedback/delays-drivers-and-competing-loops/#boundaries: nothing on the diagram changes them.

Delays in control

A delay thinking-in-diagrams.aryehnielsen.com/feedback/loops-that-amplify-loops-that-correct/#delays can sit on either half of a control loop. The **forward path** runs from the gap to the controlled variable; the **return path** runs from the controlled variable back to the gap, through the measured value.

A delay on the forward path is a correction arriving late. In estimates the Bank of England cites, the change in inflation after a change in interest rates peaks around one to two years later, so *policy interest rate* → *inflation* carries a delay. A delay on the return path is a reading arriving late: a thermometer read once an hour. Where the

controlled variable is a stock, a delay on either path is a material or signal delay

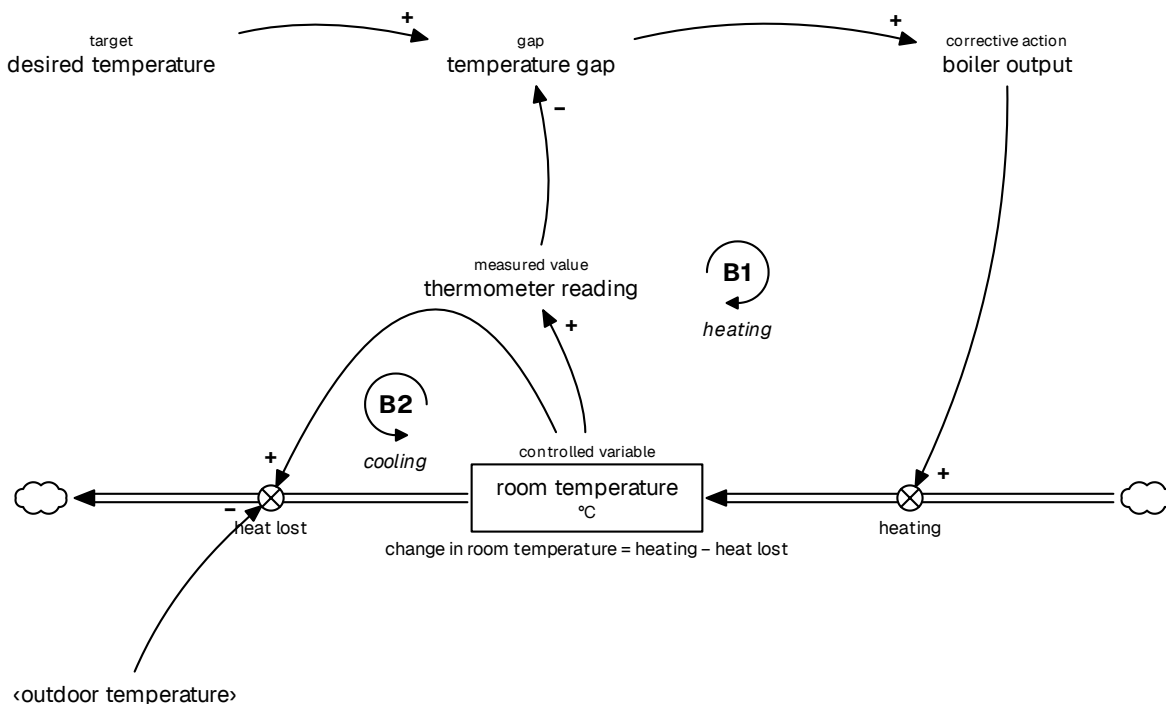
thinking-in-diagrams.aryehnielsen.com/accumulation/stocks-inside-feedback/#material-and-signal-delays.

Control with accumulation

Where the controlled variable accumulates, it is drawn as a stock

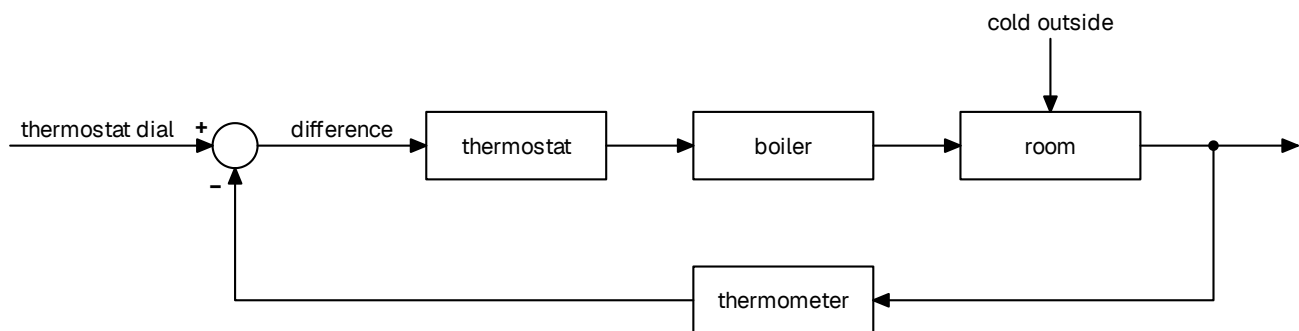
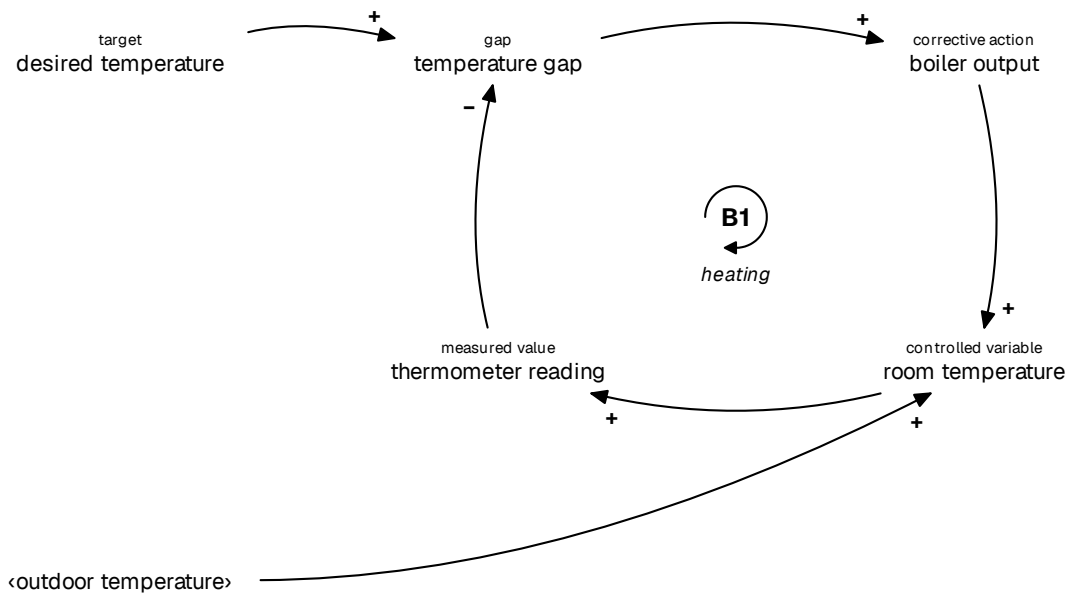
thinking-in-diagrams.aryehnielsen.com/accumulation/what-accumulates/#stocks, filled and drained by flows

thinking-in-diagrams.aryehnielsen.com/accumulation/what-accumulates/#flows, and the corrective action and external drivers reach it by signals thinking-in-diagrams.aryehnielsen.com/accumulation/what-accumulates/#signals to the flows' valves. Meadows draws the thermostat this way: the room's temperature as a stock, filled by heat from the furnace and drained by heat leaking outside.



Only the roles' words are added: *controlled variable* above the stock's box, *corrective action* above *boiler output*, whose signal reaches *heating's* valve. B1 runs through *heating*, as chapter 7's loops through stocks thinking-in-diagrams.aryehnielsen.com/accumulation/stocks-inside-feedback/#loops-through-stocks run through a flow. *Outdoor temperature* acts at *heat lost's* valve, -: the colder outside, the faster heat leaks out. *Room temperature* → *heat lost* closes a second balancing loop, B2 *cooling*: the warmer the room, the faster it loses heat.

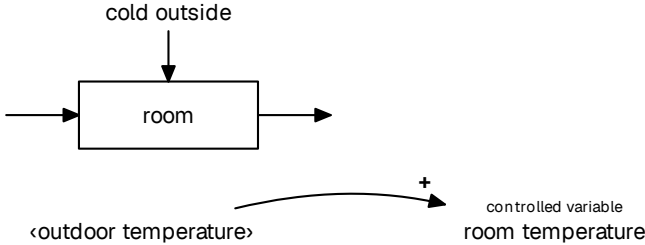
The engineering block diagram



An engineer draws the same thermostat as a block diagram: a box for each part that acts, lines carrying signals between them, and a circle where two signals are subtracted.

Engineering name	In the block diagram	In a feedback control diagram
<i>setpoint</i>	the line named <i>thermostat dial</i> , marked +	the target

Engineering name	In the block diagram	In a feedback control diagram
<i>comparator</i>	the circle	the gap, which the target and the measured value both affect
<i>error</i>	the line named <i>difference</i>	the gap
<i>controller</i>	the <i>thermostat</i> box	the signal from the gap to the corrective action
<i>actuator</i>	the <i>boiler</i> box	the corrective action, <i>boiler output</i>
<i>plant</i>	the <i>room</i> box	the controlled variable, <i>room temperature</i>
<i>sensor</i>	the <i>thermometer</i> box	the measured value, <i>thermometer reading</i>

Engineering name	In the block diagram	In a feedback control diagram
<i>disturbance</i>	the line named <i>cold outside</i>	an external driver acting on the controlled variable
		

An engineer's box is a part that acts, such as the boiler; this book's box is a stock, and a part that acts appears only through the quantity it changes, such as *boiler output*.

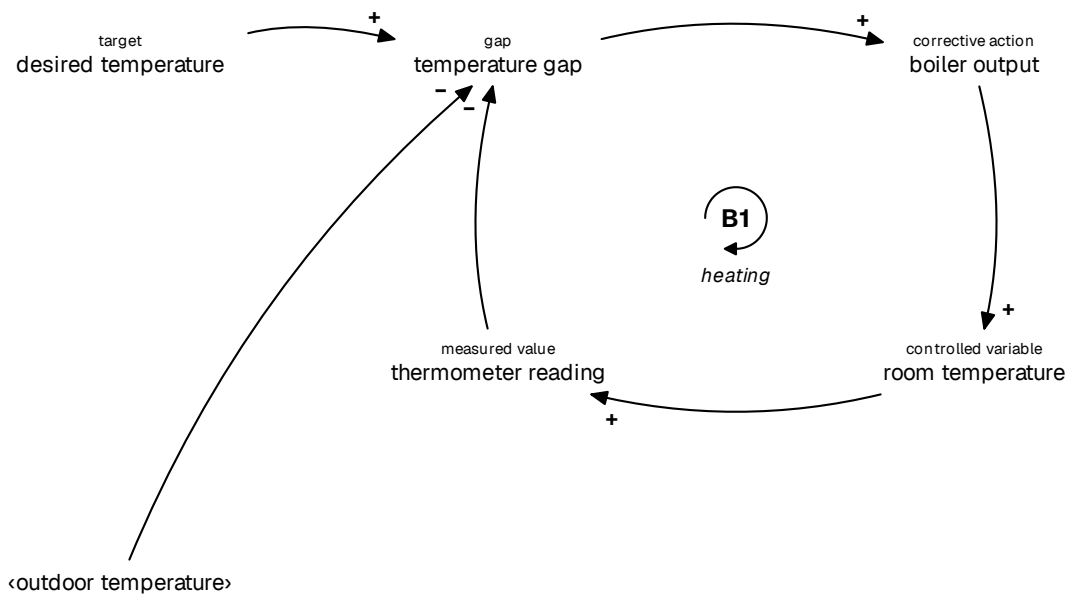
What stays informal

When no one chooses the value a quantity settles at, draw it as a causal loop diagram: a cup of tea cools toward the room's temperature through a balancing loop with no target, reading or corrective action. When the reading and the quantity read can't come apart, write a sentence: a toilet cistern's float rides on the water, so *the cistern fills until the float shuts the valve*.

How much the corrective action changes for each degree of gap, and how fast, are numbers the diagram doesn't hold: they go in a sentence or a table beside it.

The bad diagram

What's wrong with this diagram of the house kept warm on a winter evening?

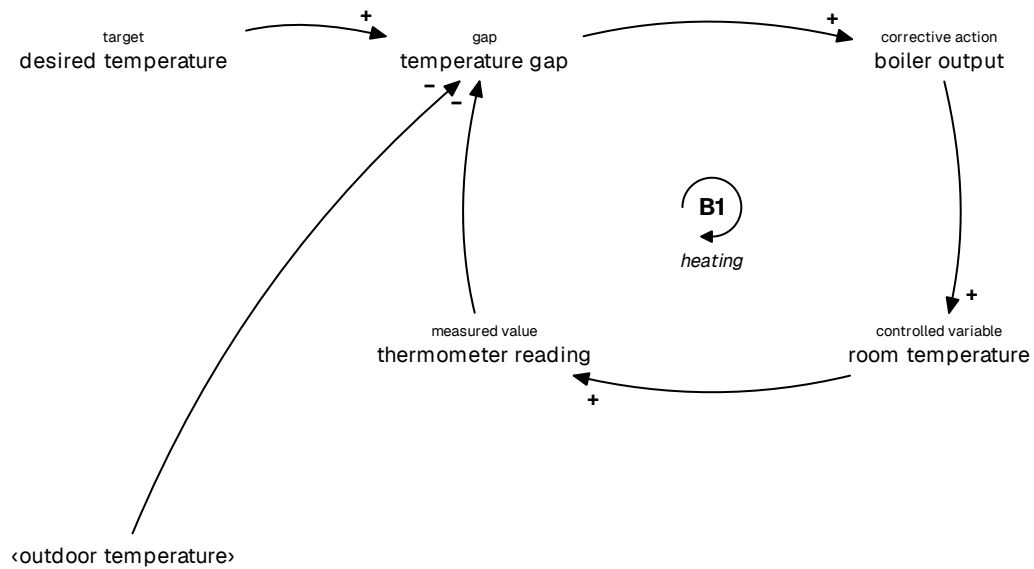
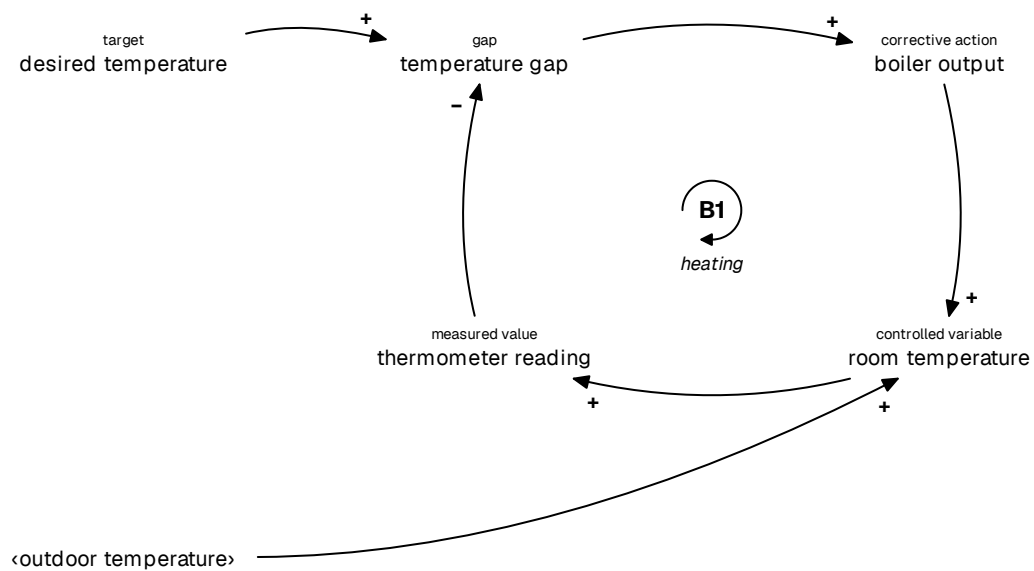


The cold outside changes the room's temperature, and the thermometer reads the room. Here the signal from *outdoor temperature* ends at the gap instead: the cold is drawn as if it changed the temperature someone wants, and the room's temperature as if only the boiler changed it. The lab's check reports:

outdoor temperature → temperature gap ends at a gap. End it at the variable the external driver changes: an external driver acts on a controlled variable, a measured value or a corrective action, never on a gap or a target.

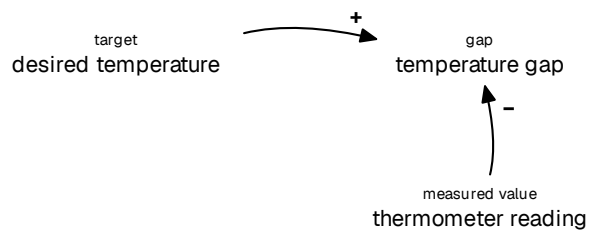
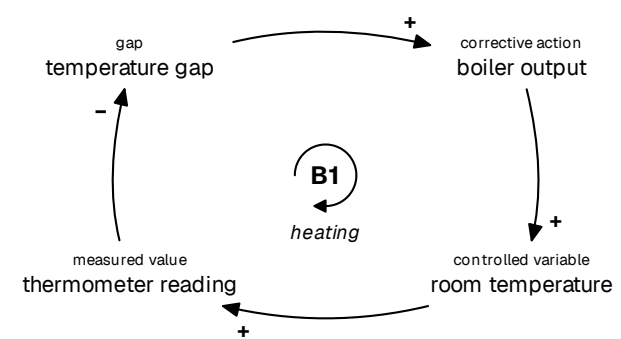
The corrected diagram

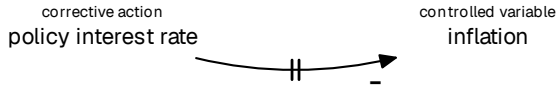
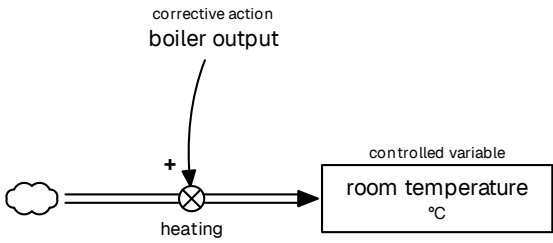
Corrected, the outdoor temperature's signal ends at *room temperature*, +, and only the target and the thermometer reading have signals into the gap.

Bad diagram**Corrected diagram**

Labels unchanged. Signals: 1 added, 1 removed.

Notation moves

Notation move	When	What it shows	Example
Write <i>target</i> above a variable	Someone chooses a value for a quantity to stay near	The chosen value, with no signal into it	<i>desired temperature</i>
			
Give the gap's two signals opposite polarities		Which way the gap runs	<i>desired temperature +, thermometer reading -</i>
Draw the measured value apart from the controlled variable		Where a reading can run late or mislead	<i>room temperature → thermometer reading</i>
			
Write <i>corrective action</i> above a quantity		What is changed to close the gap	<i>boiler output, not boiler</i>
Declare the control loop		The loop from gap to corrective action, controlled variable and measured value	<i>B1 heating</i>
			
End an external driver at the controlled variable	Something outside pushes the quantity away from its target	Where the push enters	<i>outdoor temperature → room temperature</i>
			

Notation move	When	What it shows	Example
Mark a delay on the forward or return path	A correction or a reading arrives late	Which half of the loop runs late	<i>policy interest rate → inflation</i>
			
Draw the controlled variable as a stock	It accumulates	The flows the corrective action and external drivers reach	<i>room temperature, filled by heating</i>
			

Check your understanding

CHECK YOUR UNDERSTANDING

A hearing aid turns its volume down when the sound reaching its wearer's ear grows louder than the loudness an audiologist set, and up when it grows quieter. A bus passes in a noisy street. In a feedback control diagram of the hearing aid, which variable does the bus's noise act on?

a

 the loudness at the wearer's ear

b

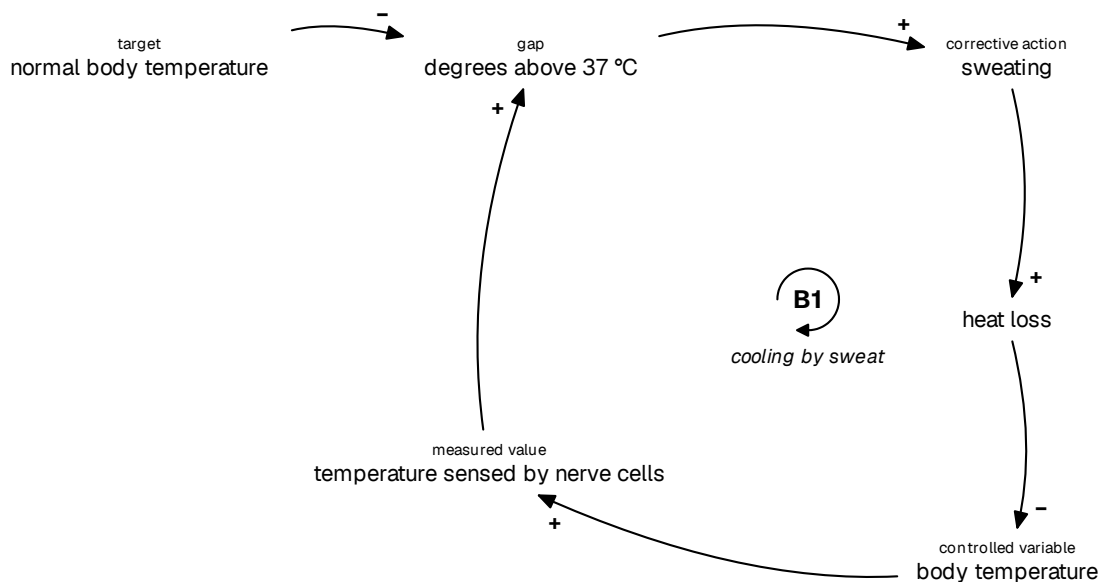
 the gap between the loudness set and the loudness read

c

 the hearing aid's volume

Feedback: Answers, chapter 8

Body temperature regulation, redrawn



Redrawn from OpenStax, Anatomy and Physiology 2e, section 1.6, “Homeostasis”, the copy on LibreTexts

[med.libretexts.org/Bookshelves/Anatomy_and_Physiology/Anatomy_and_Physiology_2e_\(OpenStax\)/01%3A_Levels_of_Organization/01%3A_An_Introduction_t](https://med.libretexts.org/Bookshelves/Anatomy_and_Physiology/Anatomy_and_Physiology_2e_(OpenStax)/01%3A_Levels_of_Organization/01%3A_An_Introduction_to_the_Human_Body/1.06%3A_Homeostasis)

, Figure 1.10, panel (b), Body temperature regulation. CC BY 4.0 creativecommons.org/licenses/by/4.0/.

Panel (b) alone, its five boxes drawn as variables with roles: body temperature exceeds 37 °C as body temperature, the controlled variable, and degrees above 37 °C, the gap; nerve cells in skin and brain as temperature sensed by nerve cells, the measured value; sweat glands throughout body as sweating, the corrective action; increased heat loss as heat loss; the temperature regulatory center in brain as the signal from the gap to sweating; normal body temperature, from its text, added as the target; polarities added and the loop named; its heavy red lines drawn as thin signals, and its colors left out.

QUESTION 1 OF 3

OpenStax names the temperature regulatory center in brain a control center, the part that compares a value with its normal range and activates the response; this book draws that work as the signal from the gap to the corrective action. Which part of the redrawing is it here?

- a Temperature sensed by nerve cells, since the center receives the nerve cells' reading.
- b The signal from degrees above 37 °C to sweating, with its +.
- c Normal body temperature, since the center holds the value of 37 °C.

QUESTION 2 OF 3

OpenStax names the nerve cells a sensor, which this book draws as a measured value, and the sweat glands an effector, a corrective action here. Why are those variables named temperature sensed by nerve cells and sweating, not nerve cells and sweat glands?

- a Roles are written above the names, so naming the organs would repeat the roles.
- b A variable is a quantity that can rise or fall: a reading and sweating can, while cells and glands are things.
- c The body has too many nerve cells and sweat glands to count.

QUESTION 3 OF 3

Panel (b) begins with body temperature exceeding 37 °C and draws nothing that raises it. What would a hot day or a run add to the redrawing?

- a A signal from the hot day to degrees above 37 °C, since heat widens the gap.
- b A second target, since the body holds a higher temperature during a run.
- c An external driver, its signal ending at body temperature.

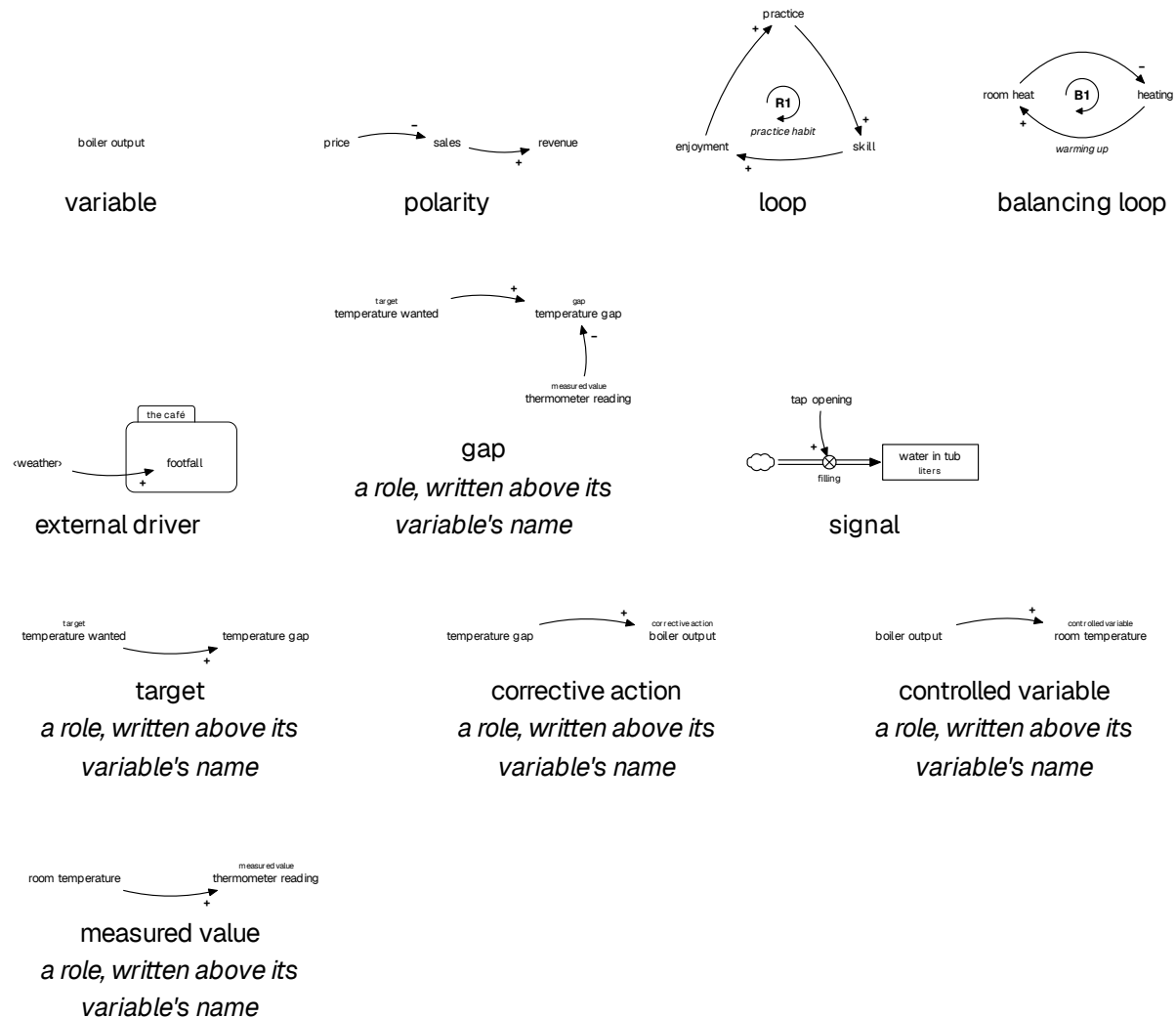
Feedback: Answers, chapter 8

Exercises

Passing the checks means meeting the brief, not being right.

FC 01 Fresh air in a choir's rehearsal room

Your palette



FC 01 Fresh air in a choir's rehearsal room

One balancing loop that holds a target

Reasoning ●○○○○ 1 of 5 Polish ●○○○○ 1 of 5

Forty singers rehearse for two hours in a room with its windows shut, and every breath adds carbon dioxide to the air. A meter on the wall shows the carbon dioxide in the air, in parts per million. The caretaker has set the ventilation fan to hold the air near 1,000 parts per million: the further the meter's reading rises above that, the faster the fan runs, and the faster it runs, the more carbon dioxide it carries out of the room.

The brief

- ☐ Draw one control loop of five variables, each with its part: the target, the gap, the fan's speed as the corrective action, the carbon dioxide in the air as the controlled variable, and the meter's reading as the measured value.
- ☐ Declare the control loop balancing.
- ☐ Draw the singers' breathing as an external driver acting on the carbon dioxide in the air.
- ☐ The fan's speed and the carbon dioxide in the air are two variables.

Your palette

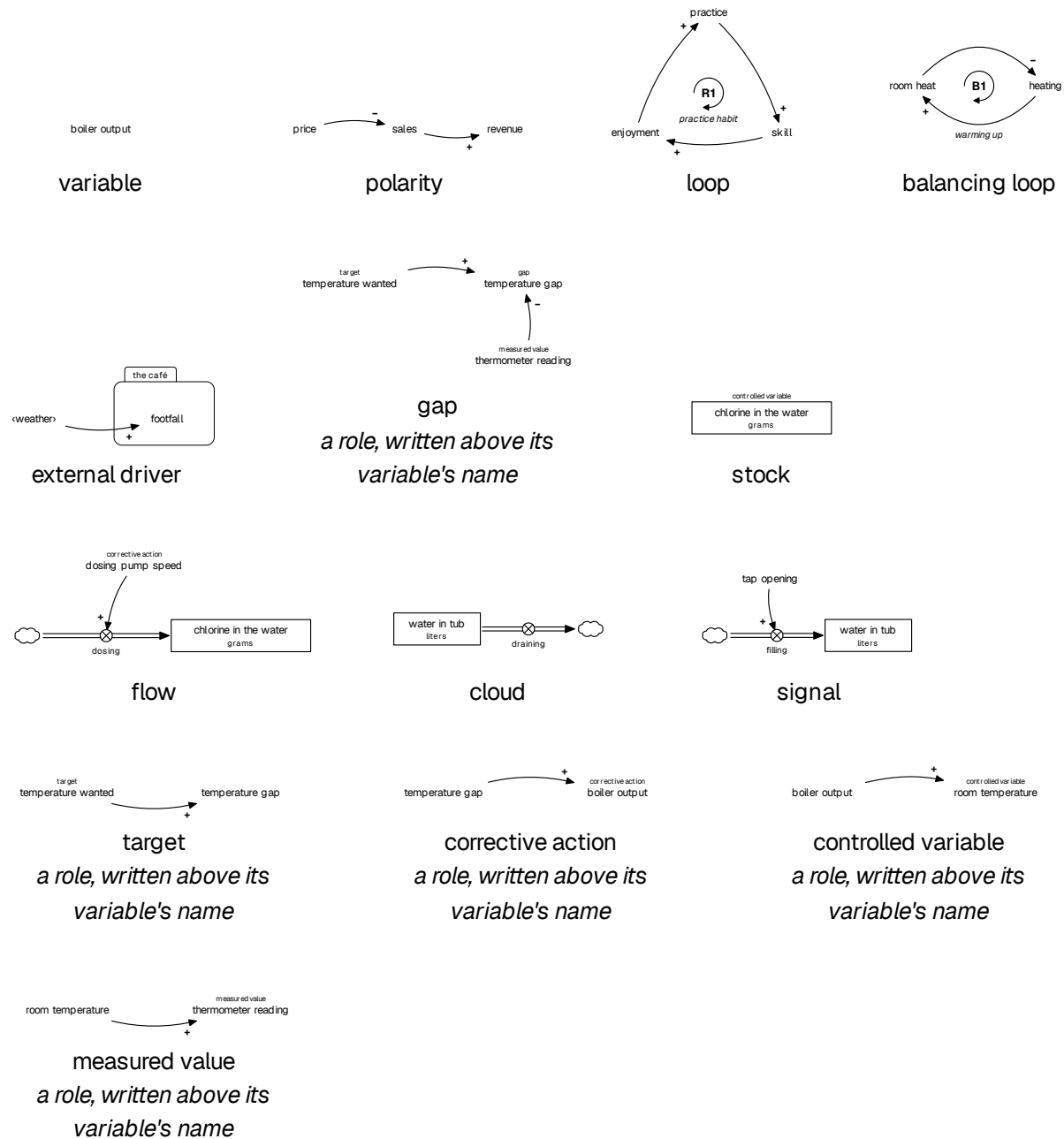
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Draw here

Grid area for drawing the control loop diagram.

FC 02 Chlorine in a town's outdoor swimming pool

Your palette



FC 02 Chlorine in a town's outdoor swimming pool

A target, a corrective action, and what uses it up

Reasoning ●○○○○ 1 of 5 Polish ●●○○○ 2 of 5

A town's outdoor swimming pool holds about 500 cubic meters of water, and the staff keep about 750 grams of chlorine in the water. A dosing pump adds chlorine from a tank: the faster it runs, the faster chlorine goes in. Sunshine and swimmers use chlorine up, faster on hot, crowded afternoons. Every two hours the staff test the water and set the pump's speed by how far the result falls short of 750 grams. Count the chlorine in grams, and time in hours.

The brief

- ☐ Draw the chlorine in the water as one stock, the controlled variable.
- ☐ Draw sunshine and swimmers as an external driver acting on the flow that uses chlorine up.
- ☐ Close one control loop through the flow that adds chlorine: the gap, the pump's speed, the chlorine in the water and the test result.
- ☐ The target and the test result name the same quantity, in grams.

Your palette

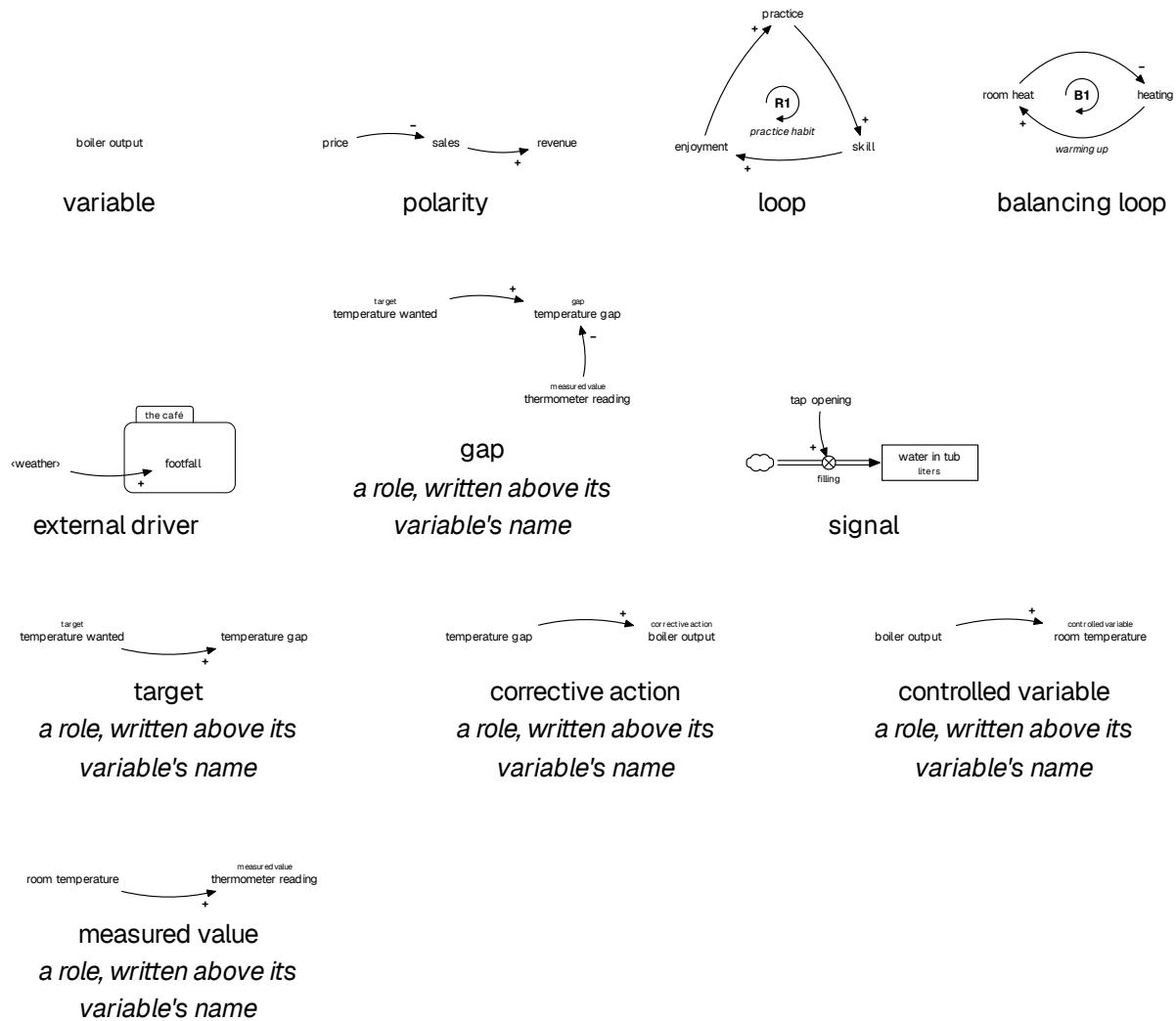
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Draw here

Grid area for drawing the diagram.

FC 03 A kayaker crossing a river

Your palette



FC 03 A kayaker crossing a river

An external driver acting on the controlled variable

Reasoning ●●○○○ 2 of 5 Polish ●●○○○ 2 of 5

A kayaker is learning to cross a river. She aims the bow at a tree on the far bank, and the current pushes the bow downstream, away from the tree. She sees how far the bow has swung off the tree and takes extra strokes on the downstream side, which turn the bow back upstream, until it points at the tree again. Halfway across she picks a new tree. Count a heading as an angle: the further upstream the bow points, the larger the angle.

The brief

- ☐ Draw the current's push as an external driver acting on the boat's heading.
- ☐ Close one control loop: the gap, her extra strokes, the boat's heading and the heading as she sees it.
- ☐ Draw one target: the heading to the tree she aims at.
- ☐ The new tree halfway across is her choice: no signal ends at the target.

Your palette

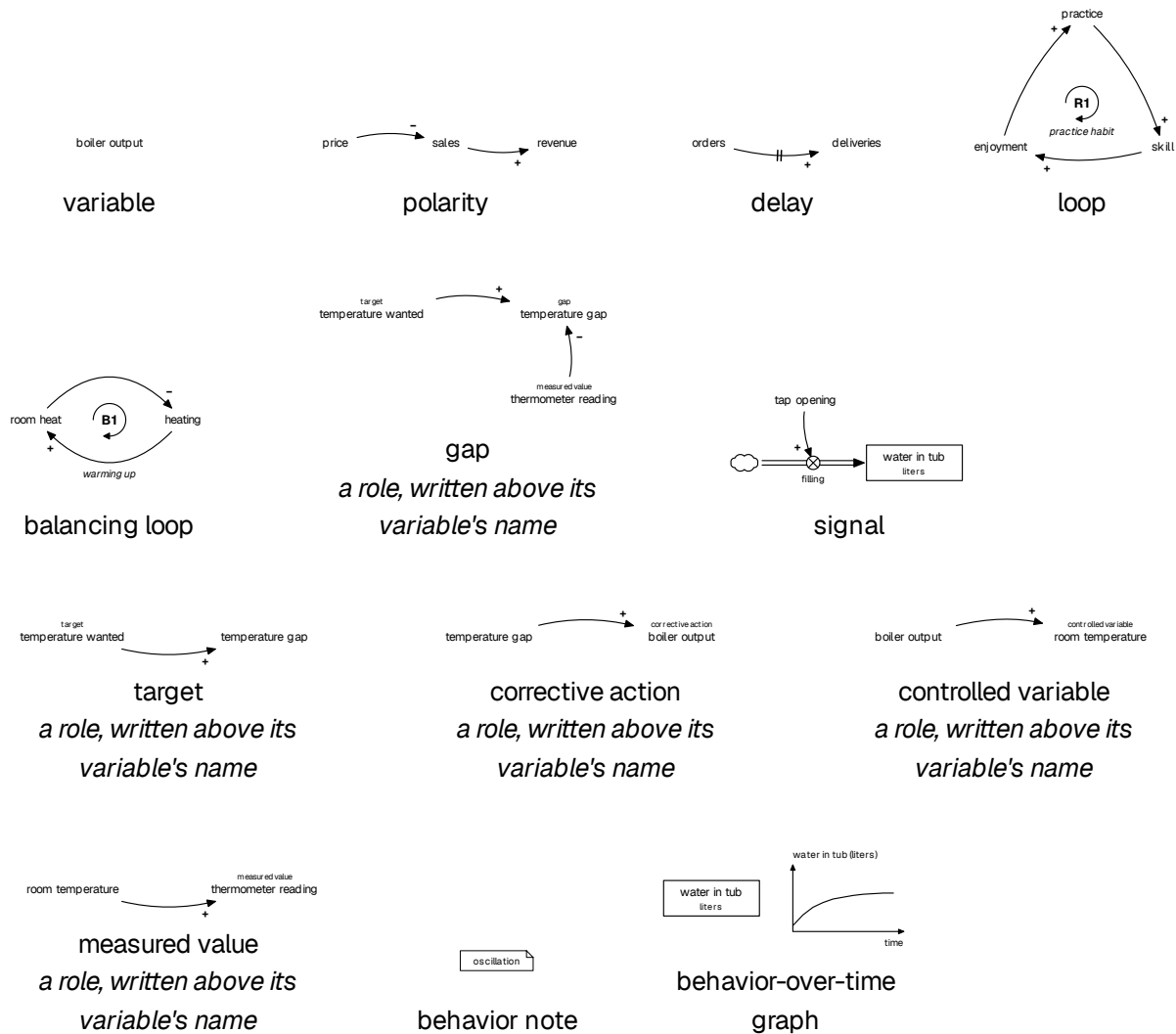
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Draw here

Grid area for drawing.

FC 04 A shower whose hot water arrives late

Your palette



FC 04 A shower whose hot water arrives late

A corrective action that arrives late

Reasoning ●●○○○ 2 of 5 Polish ●●●○○ 3 of 5

Sofia wants her morning shower at about 38 °C. After a turn of the tap, the water at the shower head changes about five seconds later, once the hot water reaches it. She feels the water, and while it feels too cold she keeps turning the tap toward hot. By the time the hot water arrives she has turned the tap too far, so the water runs too hot; she turns the tap back, and the water swings too hot and too cold before it settles near 38 °C.

The brief

- ☐ Mark the seconds between a turn of the tap and the water at the shower head as a delay on the forward path.
- ☐ Close one control loop: the gap, the tap, the water temperature at the head and how hot the water feels.
- ☐ Add a behavior-over-time graph of the water temperature at the head, overshooting and swinging, with a line at the temperature she wants.
- ☐ The delay sits between the tap and the water at the head, not between the water and her skin.

Your palette

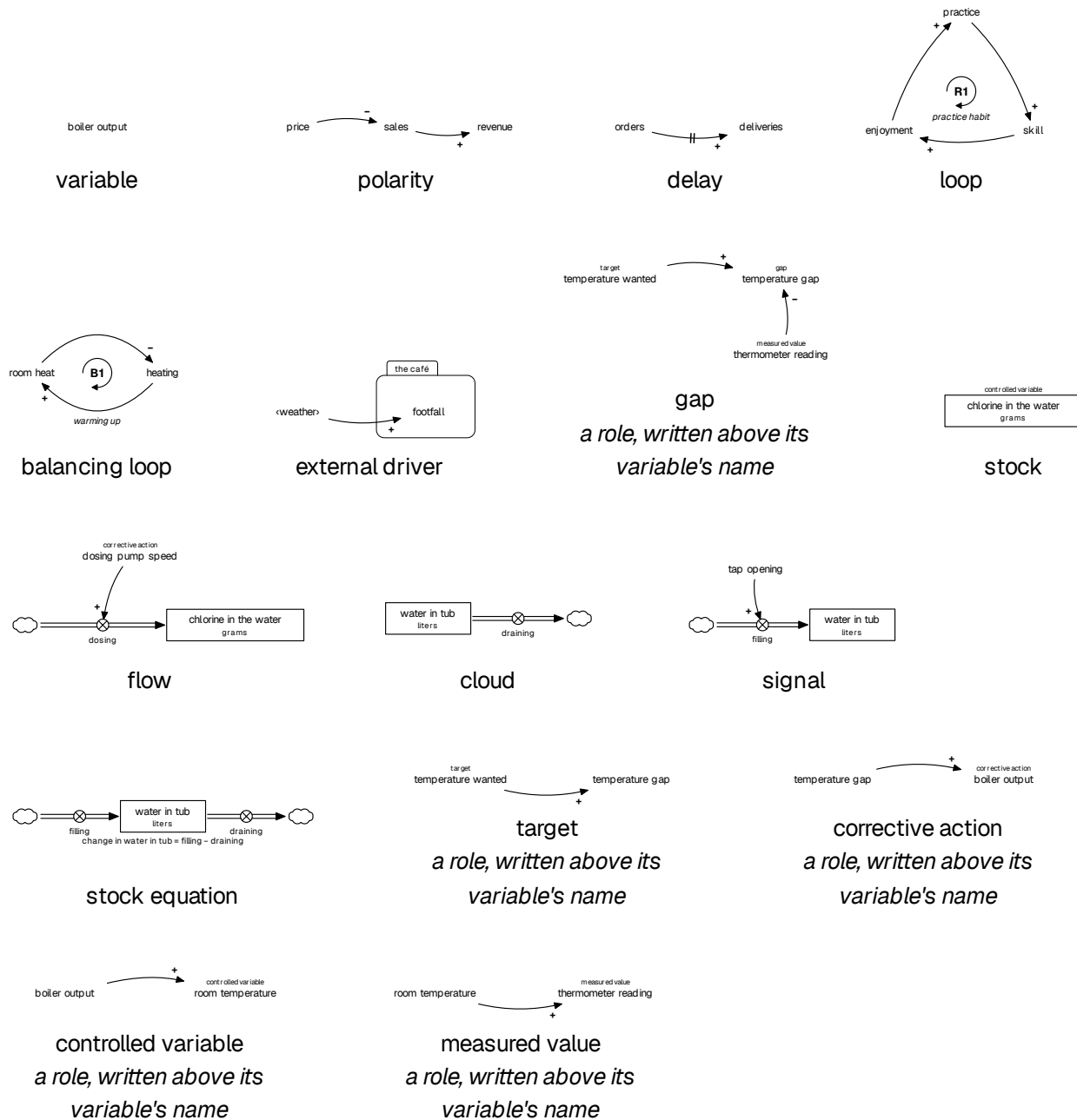
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Grid area for drawing.

FC 05 Elephants in a national park

Your palette



Control with accumulation

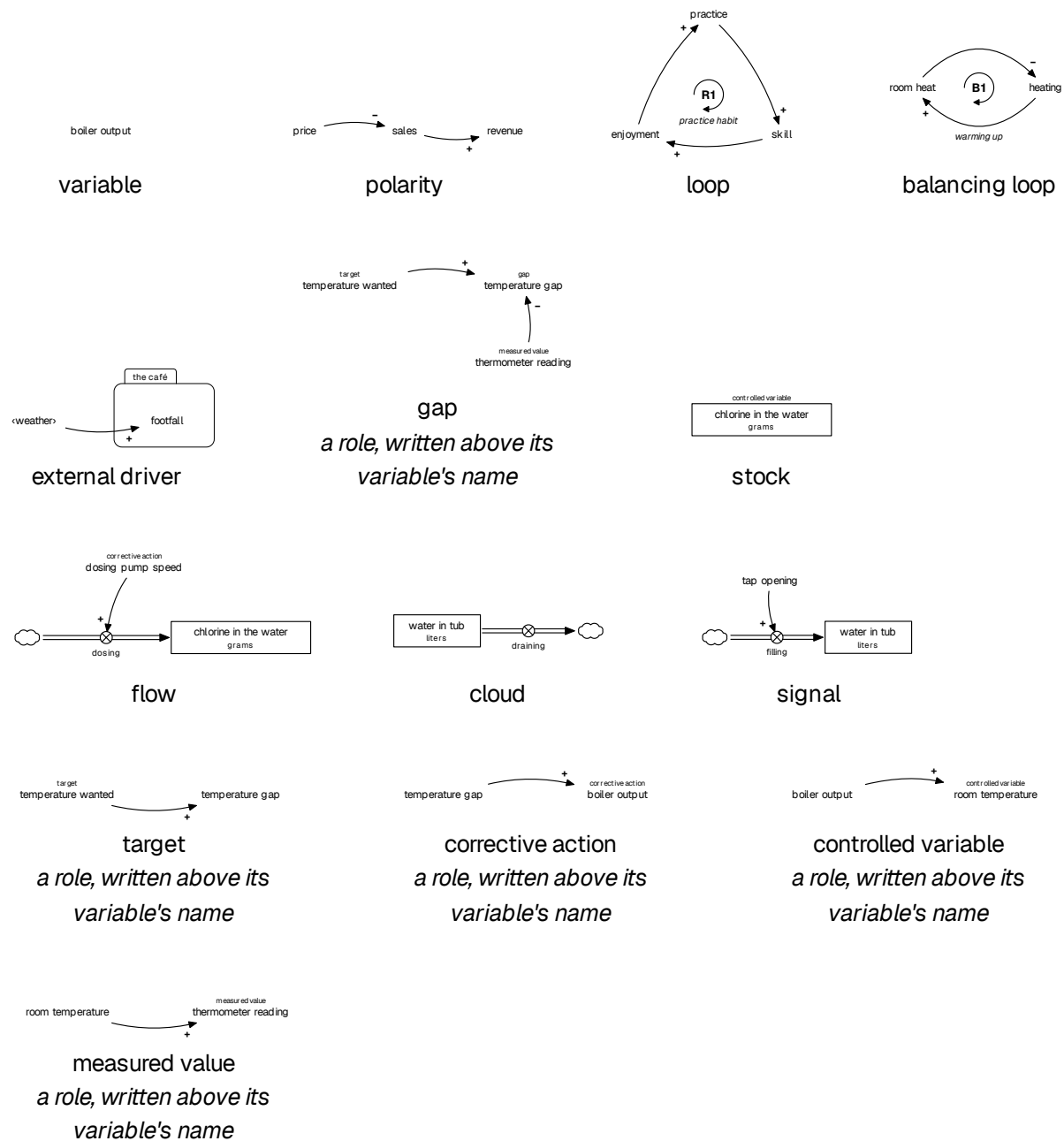
A national park's managers aim to hold its elephants near 2,000. In this park about 150 calves are born each year and about 60 elephants die, more in a year of drought. Every two years a survey plane counts the herd. From the latest count the managers approve moving elephants to other parks: the further the count is above 2,000, the more moves they approve. Moves approved this year happen the next year, when the elephants are caught and taken away by truck. Count the herd in elephants, and time in years.

- ☐ Draw the elephants in the park as one stock, the controlled variable, counted in elephants.
- ☐ Mark the year between moves approved and elephants moved as a delay on the forward path.
- ☐ Close one control loop through the flow of elephants moved: the gap, moves approved, the elephants in the park and the aerial count.
- ☐ Moves approved are a variable, and elephants moved the flow: the year lies between them.

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CS 08 Kelsham Primary School: the governors and the reserve

Your palette



A stock held to a target, with staff hours as the corrective action

Reasoning ●●●○○ 3 of 5 Polish ●●●○○ 3 of 5

Tom Hale and the governors hold the school's reserve to at least £60,000; in October 2026 it stood at £96,000. Funding arrives through the school year, £4,800 for each pupil at the October count before it and £140,000 whatever the school's size, and pay goes out, a teacher costing the school £52,000 a year. Each term the governors read the reserve in the budget report, and the further it reads below £60,000, the more staff hours they cut, a teaching assistant's before a teacher's. The governors set neither the funding for each pupil nor the pupils on roll. Count the reserve in pounds, and time in years.

The brief

- ☐ Draw the school's reserve as one stock, the controlled variable, counted in pounds.
- ☐ Close one control loop through the flow of spending: the gap, staff hours cut, the reserve and the reserve in the budget report.
- ☐ Draw funding for each pupil and the pupils on roll as external drivers acting on the flow of funding.
- ☐ The target and the reserve in the budget report are both counted in pounds, so the gap compares one quantity.

Your palette

On the page before this sheet.

Draw here

Sources

- Donella H. Meadows, *Thinking in Systems: A Primer* (Chelsea Green, 2008), chapter 2, *A Brief Visit to the Systems Zoo*, on the thermostat drawn as one stock, the room's temperature, with two competing balancing loops.
- Karl Johan Åström and Richard M. Murray, *Feedback Systems: An Introduction for Scientists and Engineers* fbswiki.org/wiki/index.php/Main_Page, second edition (Princeton University Press, 2021), chapter 1, on feedback, the parts of a feedback system and a thermostat's on-off rule, and chapter 3, on how engineers draw boxes and lines.
- Stephen Boyd, "Feedback Control Systems: Static Analysis" stanford.edu/~boyd/ee102/ctrl-static.pdf, lecture 12 of EE102 (Stanford University), on the names engineers give a feedback system's parts.
- James K. Roberge, *Operational Amplifiers: Theory and Practice* [eng.libretexts.org/Bookshelves/Electrical_Engineering/Electronics/Operational_Amplifiers:_Theory_and_Practice_\(Roberge\)/02:_Properties_and_Modeling_of_Feedback_Systems/2.02:_SYMBOLLOGY](https://eng.libretexts.org/Bookshelves/Electrical_Engineering/Electronics/Operational_Amplifiers:_Theory_and_Practice_(Roberge)/02:_Properties_and_Modeling_of_Feedback_Systems/2.02:_SYMBOLLOGY) (MIT), section 2.2, the source of the engineering name for where the target and the measured value meet.
- Bank of England, *Monetary policy* www.bankofengland.co.uk/monetary-policy, on the 2% target the government sets.
- Bank of England, *What is happening with interest rates in the UK?* www.bankofengland.co.uk/explainers/current-interest-rate, on gas prices after Russia's invasion of Ukraine and the rate rises from the end of 2021.
- Bank of England, *Monetary Policy Report, August 2024* www.bankofengland.co.uk/-/media/boe/files/monetary-policy-report/2024/august/monetary-policy-report-august-2024.pdf, box C, on the impact of interest rates on inflation peaking at around one to two years.

Answers

Chapter 8 · Sense, Compare, Correct

A kitchen fridge's thermostat reads the air by the door. Each time the door opens, warm kitchen air reaches the thermostat first and the compressor starts, while the food at the back stays cold; by evening the milk on the back shelf has frozen. In a feedback control diagram of the fridge, which variable is the measured value?

- a the temperature of the food on the back shelf
Not quite. That is the controlled variable: the temperature someone wants held near the dial's setting. Nothing in the fridge reads it.
- b the thermostat's reading of the air by the door
Yes. The thermostat reads the air by the door, a variable of its own, with a signal from the food's temperature. The open door changes the reading far more than the food, so the gap opens while the food is already cold, and the compressor runs on.
- c the setting on the dial
Not quite. The dial's setting is the target: a value someone chose, with a signal into the gap and none into it.

A hearing aid turns its volume down when the sound reaching its wearer's ear grows louder than the loudness an audiologist set, and up when it grows quieter. A bus passes in a noisy street. In a feedback control diagram of the hearing aid, which variable does the bus's noise act on?

- a the loudness at the wearer's ear
Yes. The noise makes the sound at the ear louder: an external driver acting on the controlled variable. The reading follows it, the gap opens, and the hearing aid turns its volume down.
- b the gap between the loudness set and the loudness read
Not quite. A signal from the noise into the gap would draw the bus changing the loudness the audiologist set. The gap changes only because the reading of the ear's loudness does.
- c the hearing aid's volume
Not quite. The volume is the corrective action. The noise changes it only through the loudness at the ear, the reading and the gap.

QUESTION 1 OF 3

OpenStax names the temperature regulatory center in brain a control center, the part that compares a value with its normal range and activates the response; this book draws that work as the signal from the gap to the corrective action. Which part of the redrawing is it here?

- a Temperature sensed by nerve cells, since the center receives the nerve cells' reading.
Not quite. That variable is the reading itself, the measured value. The center acts once the reading is compared with the target: from the gap on.
- b The signal from degrees above 37 °C to sweating, with its +.
Yes. The comparison is the gap itself, read from the target and the measured value; what the center then does, more sweating for each degree above 37 °C, is the signal from the gap to sweating and its polarity. The center is an organ, and only quantities are drawn.
- c Normal body temperature, since the center holds the value of 37 °C.
Not quite. Normal body temperature is the target, the value chosen to stay near, with no signal into it. Comparing readings with it and driving the sweating is the signal from the gap to sweating.

OpenStax names the nerve cells a sensor, which this book draws as a measured value, and the sweat glands an effector, a corrective action here. Why are those variables named temperature sensed by nerve cells and sweating, not nerve cells and sweat glands?

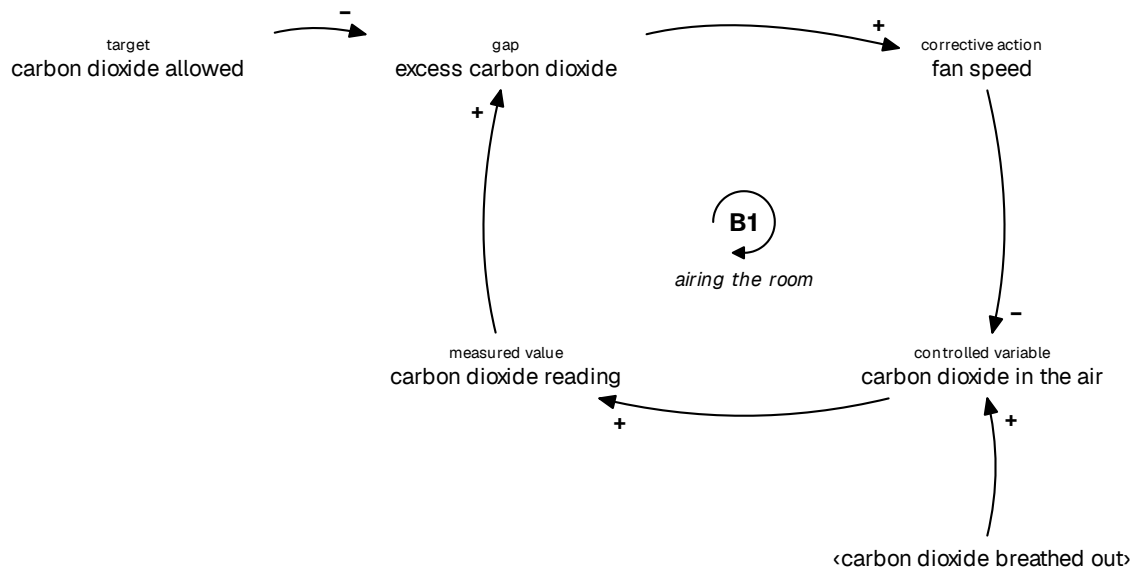
- a** Roles are written above the names, so naming the organs would repeat the roles.
Not quite. A role names the part a variable plays; the name says which quantity plays it. Nerve cells and sweat glands are things, so they appear only through quantities they produce.
- b** A variable is a quantity that can rise or fall: a reading and sweating can, while cells and glands are things.
Yes. More temperature sensed and more sweating pass the more test. More nerve cells names a different quantity, how many there are, which the loop never changes. A part that acts appears through the quantity it changes, as boiler output stands for the boiler.
- c** The body has too many nerve cells and sweat glands to count.
Not quite. They could be counted, but their number is not what rises and falls as the body heats and cools: the reading and the sweating are.

QUESTION 3 OF 3

Panel (b) begins with body temperature exceeding 37 °C and draws nothing that raises it. What would a hot day or a run add to the redrawing?

- a** A signal from the hot day to degrees above 37 °C, since heat widens the gap.
Not quite. An external driver never acts on a gap. Heat raises body temperature, and the gap widens as the nerve cells read the rise.
- b** A second target, since the body holds a higher temperature during a run.
Not quite. The target stays at 37 °C; what changes is the push away from it. Nothing in the figure or its text moves the target.
- c** An external driver, its signal ending at body temperature.
Yes. Heat from the air or from working muscles pushes body temperature away from 37 °C and isn't pushed back by it: an external driver acting on the controlled variable, as outdoor temperature acts on room temperature in a house.

FC 01 Fresh air in a choir's rehearsal room



This is one defensible answer, not the only one. Yours can differ and still hold up: the lab's checks show whether it has the brief's structure.

Five variables, each with its part: carbon dioxide allowed is the target, excess carbon dioxide the gap, fan speed the corrective action, carbon dioxide in the air the controlled variable, and carbon dioxide reading the measured value. The gap rises with the reading (+) and falls as the target rises (-). A larger gap speeds the fan (+), a faster fan lowers the carbon dioxide in the air (-), and the reading follows the air (+): one - signal on the loop, so B1 is balancing. Carbon dioxide breathed out is an external driver acting on the air, off the loop.

Why it works

- The gap is the difference between the reading and the target, so the two signals into it have opposite polarities
- The reading is a variable apart from the air: the fan answers the meter, and the singers breathe into the air
- Fan speed is the corrective action; the carbon dioxide in the air is the controlled variable it changes
- The singers' breath acts on the air, never on the gap or the target: the caretaker sets the target
- One - signal on the loop makes it balancing, as declared

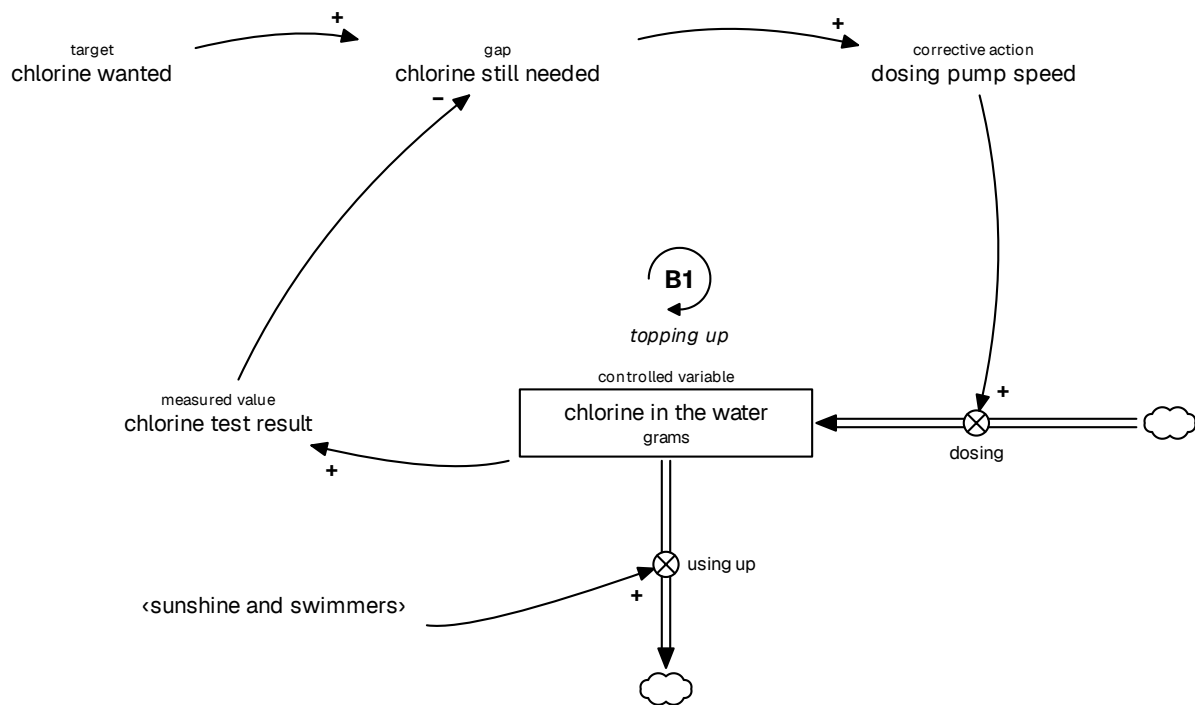
Step by step

1. Carbon dioxide in the air, the controlled variable: the quantity the caretaker set the fan to hold near 1,000 parts per million.
2. Carbon dioxide reading, the measured value, with a + signal from the air: the fan runs on what the meter on the wall shows.
3. Carbon dioxide allowed, the target, and excess carbon dioxide, the gap, read from the reading (+) and the target (-): how far the meter shows above 1,000 parts per million.
4. Fan speed, the corrective action, with a + signal from the gap and a - signal to the air, which close B1, airing the room: the larger the gap, the faster the fan runs, and the more carbon dioxide it carries out.
5. Carbon dioxide breathed out, an external driver, with a + signal to the air, off the loop: forty singers breathe into the room whatever the fan does.

What another defensible answer might vary

Another defensible answer might name the gap carbon dioxide above the target, or the external driver the singers' breath. What stays the same is five variables with their parts on one balancing loop through the gap, opposite polarities into the gap, and the breath acting on the carbon dioxide in the air.

FC 02 Chlorine in a town's outdoor swimming pool



This is one defensible answer, not the only one. Yours can differ and still hold up: the lab's checks show whether it has the brief's structure.

One stock, chlorine in the water, counted in grams: the controlled variable. Dosing fills it from a cloud and using up drains it to another, both in grams per hour. Chlorine still needed is the gap, read from chlorine wanted (+) and the chlorine test result (-); the gap sets the dosing pump's speed, whose signal ends at the dosing valve. B1 runs through the dosing flow, counted + into the stock, and has one - step, so it is balancing. Sunshine and swimmers act at the valve of using up, off the loop.

Why it works

- Chlorine moves only along the two flows; every other line is a signal
- The pump's speed is the corrective action, and its signal ends at the dosing valve, never at the stock
- The test result is a variable apart from the chlorine in the water, read from it
- Sunshine and swimmers act on the controlled variable through the flow they drain it by, never on the gap
- The one - step, from the test result to the gap, makes the loop balancing

Step by step

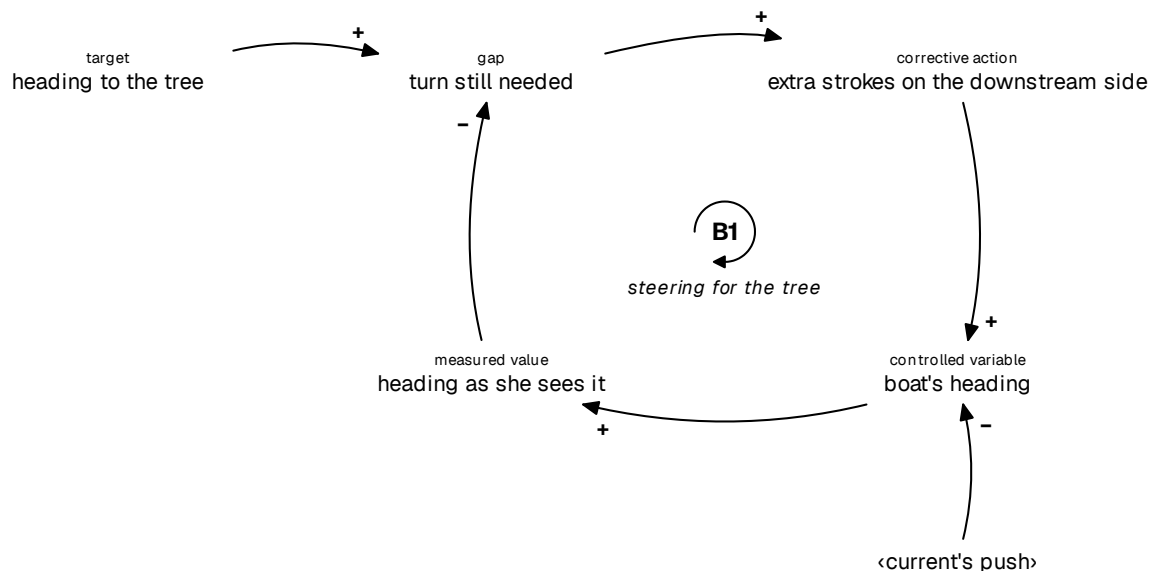
1. Chlorine in the water, the controlled variable, a stock counted in grams, with the time unit an hour: the staff keep about 750 grams in about 500 cubic meters of water.
2. Dosing, an inflow from a cloud for the tank, and using up, an outflow to a cloud: chlorine counts from when the pump adds it until sunshine and swimmers use it up.
3. Chlorine test result, the measured value, with a + signal from the stock: the staff set the pump by a test taken every two hours.
4. Chlorine wanted, the target, and chlorine still needed, the gap, read from the target (+) and the test result (-): how far the result falls short of 750 grams.

5. Dosing pump speed, the corrective action, with a + signal from the gap and a + signal to the valve of dosing, which close B1, topping up, through the stock: the further the result falls short, the faster the pump adds chlorine.
6. Sunshine and swimmers, an external driver, with a + signal to the valve of using up, off the loop: hot, crowded afternoons use chlorine up faster.

What another defensible answer might vary

Another defensible answer might name the gap chlorine short, or draw the staff's test as the measured value. What stays the same is one stock in grams with one inflow and one outflow, the time unit an hour, a balancing loop through the dosing flow, and the external driver at the valve of the flow that uses chlorine up.

FC 03 A kayaker crossing a river



This is one defensible answer, not the only one. Yours can differ and still hold up: the lab's checks show whether it has the brief's structure.

The boat's heading is the controlled variable, and the heading to the tree the target. Turn still needed is the gap, read from the target (+) and the heading as she sees it (-). The gap sets her extra strokes on the downstream side (+), the strokes turn the boat's heading upstream (+), and she sees the heading against the tree (+). B1 has one - step, so it is balancing. The current's push acts on the boat's heading (-), off the loop. When she picks a new tree, the target changes by her choice, and no signal reaches it.

Why it works

- The gap reads the target + and the heading as she sees it -: their difference is which way, and how far, she still has to turn
- The current's push acts on the boat's heading, never on the gap: a push from outside, not a change of target
- The heading as she sees it is a variable apart from the boat's heading, read from it against the tree
- No signal reaches the target: picking a new tree is her choice
- The one - step, from the heading as she sees it to the gap, makes the loop balancing

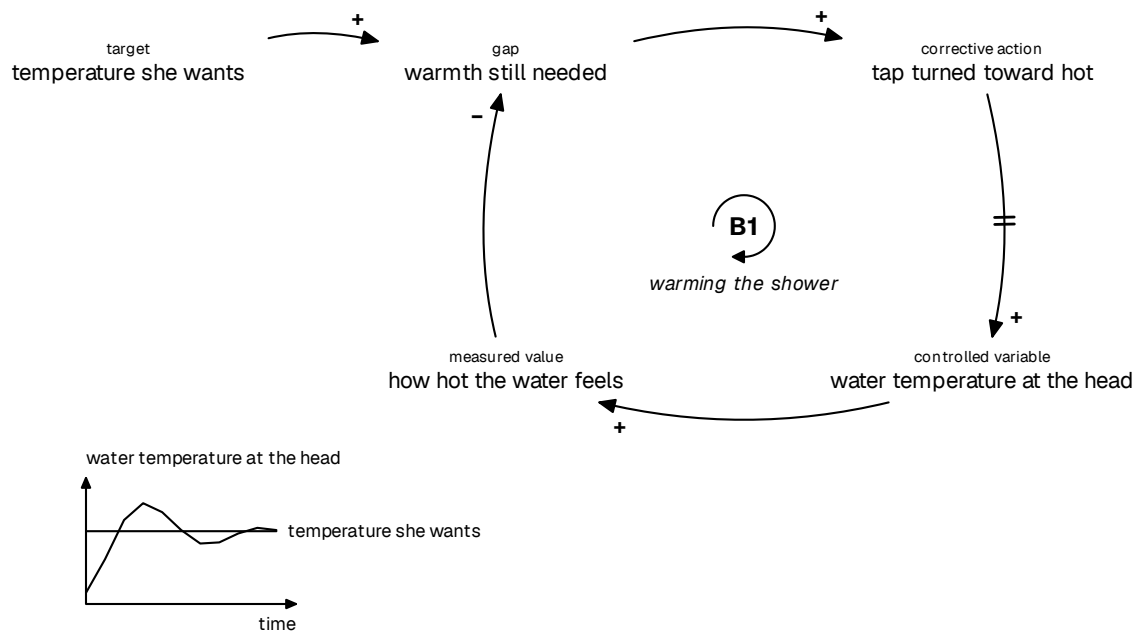
Step by step

1. The boat's heading, the controlled variable, counted as an angle that grows the further upstream the bow points.
2. Heading as she sees it, the measured value, with a + signal from the boat's heading: she judges the heading by where the bow points against the tree.
3. Heading to the tree, the target, and turn still needed, the gap, read from the target (+) and the heading as she sees it (-): the angle between where she aims and where she sees the bow pointing.
4. Extra strokes on the downstream side, the corrective action, with a + signal from the gap and a + signal to the boat's heading, which close B1, steering for the tree: she keeps stroking until the bow points at the tree again.
5. The current's push, an external driver, with a - signal to the boat's heading, off the loop: it swings the bow downstream whatever tree she aims at.

What another defensible answer might vary

Another defensible answer might count headings the other way, as how far the bow points downstream of the tree, with the gap reading the target – and the heading as she sees it +, and the current's push +. What stays the same is one target with no signal into it, a gap read with opposite polarities, one balancing control loop, and the current's push acting on the boat's heading.

FC 04 A shower whose hot water arrives late



This is one defensible answer, not the only one. Yours can differ and still hold up: the lab's checks show whether it has the brief's structure.

The water temperature at the head is the controlled variable, and the temperature she wants the target. Warmth still needed is the gap, read from the target (+) and how hot the water feels (-); it sets how far the tap is turned toward hot (+), and the tap changes the water at the head (+) five seconds later: a delay on the forward path. B1 has one – step, so it is balancing. While the hot water is on its way she keeps turning, so the water arrives too hot; she turns back, and it arrives too cold. The graph overshoots the line at the temperature she wants and swings around it, closer each time.

Why it works

- The delay is on the signal from the tap to the water at the head: the forward path, where the correction arrives late
- How hot the water feels is read from the water at the head with no delay: she feels the water as soon as it arrives
- She keeps turning the tap while the hot water is on its way, so the water overshoots, and the graph oscillates around the target
- The graph's line is drawn at the temperature she wants, solid: a dashed line marks a hypothesis
- The one – step, from how hot the water feels to the gap, makes the loop balancing

Step by step

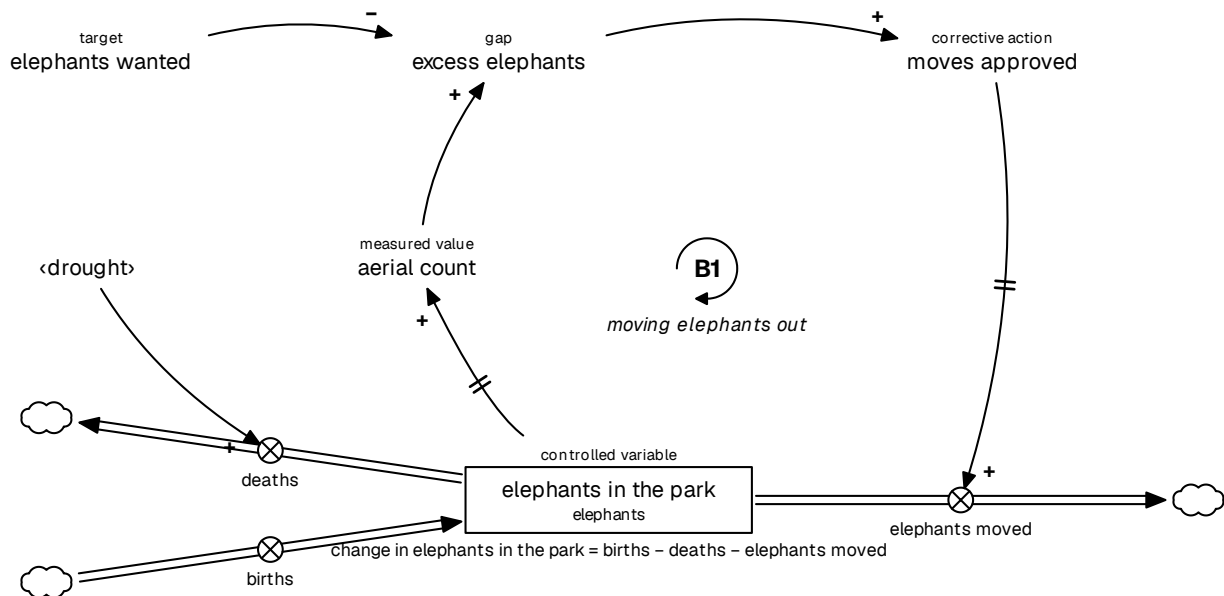
1. Water temperature at the head, the controlled variable: the water she showers in, which she wants at about 38 °C.
2. How hot the water feels, the measured value, with a + signal from the water at the head and no delay, since she stands in the water as it leaves the head.

3. Temperature she wants, the target, and warmth still needed, the gap, read from the target (+) and how hot the water feels (-): above zero while the water feels too cold, below zero once it feels too hot.
4. Tap turned toward hot, the corrective action, with a + signal from the gap and a + signal to the water at the head, delayed about five seconds while the hot water travels to the head, which close B1, warming the shower.
5. A behavior-over-time graph of the water at the head, with a solid line at the temperature she wants: each turn of the tap shows at the head only five seconds later, so the water swings too hot and too cold around the line before it settles near 38 °C.

What another defensible answer might vary

Another defensible answer might add a behavior note on the water swinging past 38 °C each way before it settles, or name the gap too cold by. What stays the same is one balancing control loop, one delay on the signal from the tap to the water at the head, and an oscillating graph of that water's temperature with a solid line at the temperature she wants.

FC 05 Elephants in a national park



This is one defensible answer, not the only one. Yours can differ and still hold up: the lab's checks show whether it has the brief's structure.

One stock, elephants in the park, counted in elephants: the controlled variable. Births fill it from a cloud; deaths and elephants moved drain it to clouds, each in elephants per year, and its stock equation is written beneath it. Excess elephants is the gap, read from elephants wanted (-) and the aerial count (+); it sets moves approved (+), whose signal reaches the valve of elephants moved a year later (+): a delay on the forward path. The aerial count reads the stock every two years: a delay on the return path. B1 runs through elephants moved, counted - out of the stock, and has one - step, so it is balancing. Drought acts at the valve of deaths, off the loop.

Why it works

- Moves approved are a variable and elephants moved the flow; the year between them is a delay on the forward path
- The aerial count is a variable apart from the elephants in the park, and the two years between counts are a delay on the return path
- Elephants enter and leave the park only along the three flows; every other line is a signal
- Drought acts on the controlled variable through the flow of deaths, never on the gap
- The one - step, elephants moved draining the stock, makes the loop balancing

Step by step

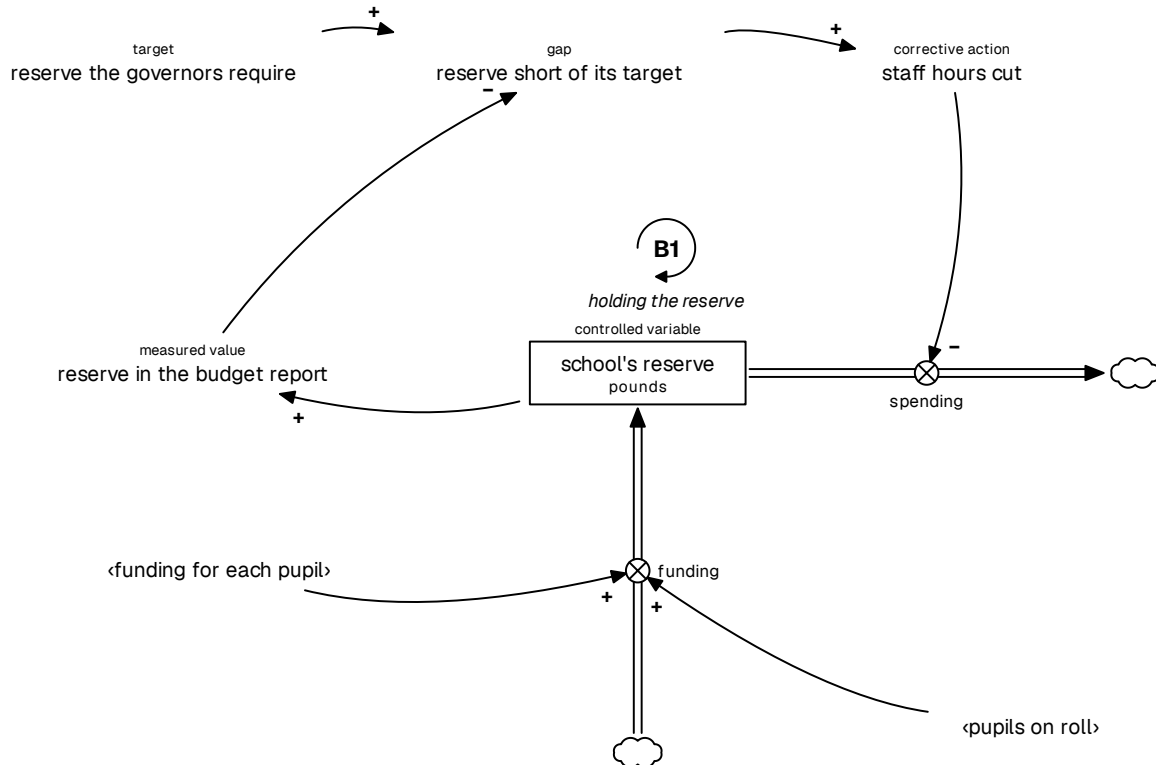
1. Elephants in the park, the controlled variable, a stock counted in elephants, with the time unit a year and its stock equation beneath it: the managers aim to hold it near 2,000.
2. Births, from a cloud, and deaths and elephants moved, each to a cloud: about 150 calves a year against about 60 deaths, so with no elephants moved the herd grows by about 90 a year.
3. Aerial count, the measured value, with a + signal from the stock, delayed since the survey plane counts the herd only every two years.

4. Elephants wanted, the target, and excess elephants, the gap, read from the aerial count (+) and the target (-): how far the latest count sits above 2,000.
5. Moves approved, the corrective action, with a + signal from the gap and a + signal to the valve of elephants moved, delayed a year while the elephants are caught and taken away by truck, which close B1, moving elephants out, through the stock.
6. Drought, an external driver, with a + signal to the valve of deaths, off the loop: more elephants die in a dry year, whatever the managers approve.

What another defensible answer might vary

Another defensible answer might add a signal from the stock to the valve of births, with a reinforcing loop of its own, or name the gap elephants over the number. What stays the same is one stock in elephants with births in and two flows out, the time unit a year, one balancing control loop through elephants moved, one delay between moves approved and elephants moved, and drought at the valve of deaths.

CS 08 Kelsham Primary School: the governors and the reserve



This is one defensible answer, not the only one. Yours can differ and still hold up: the lab's checks show whether it has the brief's structure.

One stock, the school's reserve, counted in pounds: the controlled variable. Funding fills it from a cloud and spending drains it to another, both in pounds per year. Reserve short of its target is the gap, read from reserve the governors require (+) and the reserve in the budget report (-); the gap raises staff hours cut (+), whose signal lowers the valve of spending (-). B1, holding the reserve, runs through spending, counted - out of the stock, and has three - steps, so it is balancing. Funding for each pupil and the pupils on roll act at the valve of funding, off the loop: £4,800 for each of 88 pupils and £140,000 come to £562,400 a year.

Why it works

- Money moves only along funding and spending; every other line is a signal
- Staff hours cut is the corrective action, and its signal ends at the valve of spending, never at the stock
- The reserve in the budget report is a variable apart from the reserve, read from it each term
- The two external drivers act on the reserve at the valve of funding, never on the gap
- Three - steps, from the report to the gap, from the cut to spending and along spending, make the loop balancing

Step by step

1. The school's reserve, the controlled variable, a stock counted in pounds, with the time unit a year: £96,000 in October 2026.
2. Funding, an inflow from a cloud for the county council, and spending, an outflow to a cloud for pay and bills: money counts in the reserve from when it arrives until it is spent.

3. Reserve in the budget report, the measured value, with a + signal from the stock: the governors read it each term.
4. Reserve the governors require, the target, and reserve short of its target, the gap, read from the target (+) and the report (-): how far the report reads below £60,000.
5. Staff hours cut, the corrective action, with a + signal from the gap and a – signal to the valve of spending, which close B1, holding the reserve, through the stock: the further the report reads below £60,000, the more hours the governors cut and the less the school spends.
6. Funding for each pupil and pupils on roll, two external drivers, with + signals to the valve of funding, off the loop: the county council sets the £4,800, and parents and births set the roll.

What another defensible answer might vary

Another defensible answer might draw one external driver, funding for the school year, with the rate for each pupil and the roll folded into it, or name the corrective action staff hours paid for, with a + signal to the valve of spending and the gap read the other way round. What stays the same is one stock in pounds with funding in and spending out, the time unit a year, one balancing control loop through spending, and the external drivers acting at the valve of funding.