# Supplemental Material

*CBE—Life Sciences Education*

Kiesewetter and Schmiemann

*Supplemental Materials for*

# Understanding Homeostatic Regulation - The Role of Relationships and Conditions in Feedback Loop Reasoning

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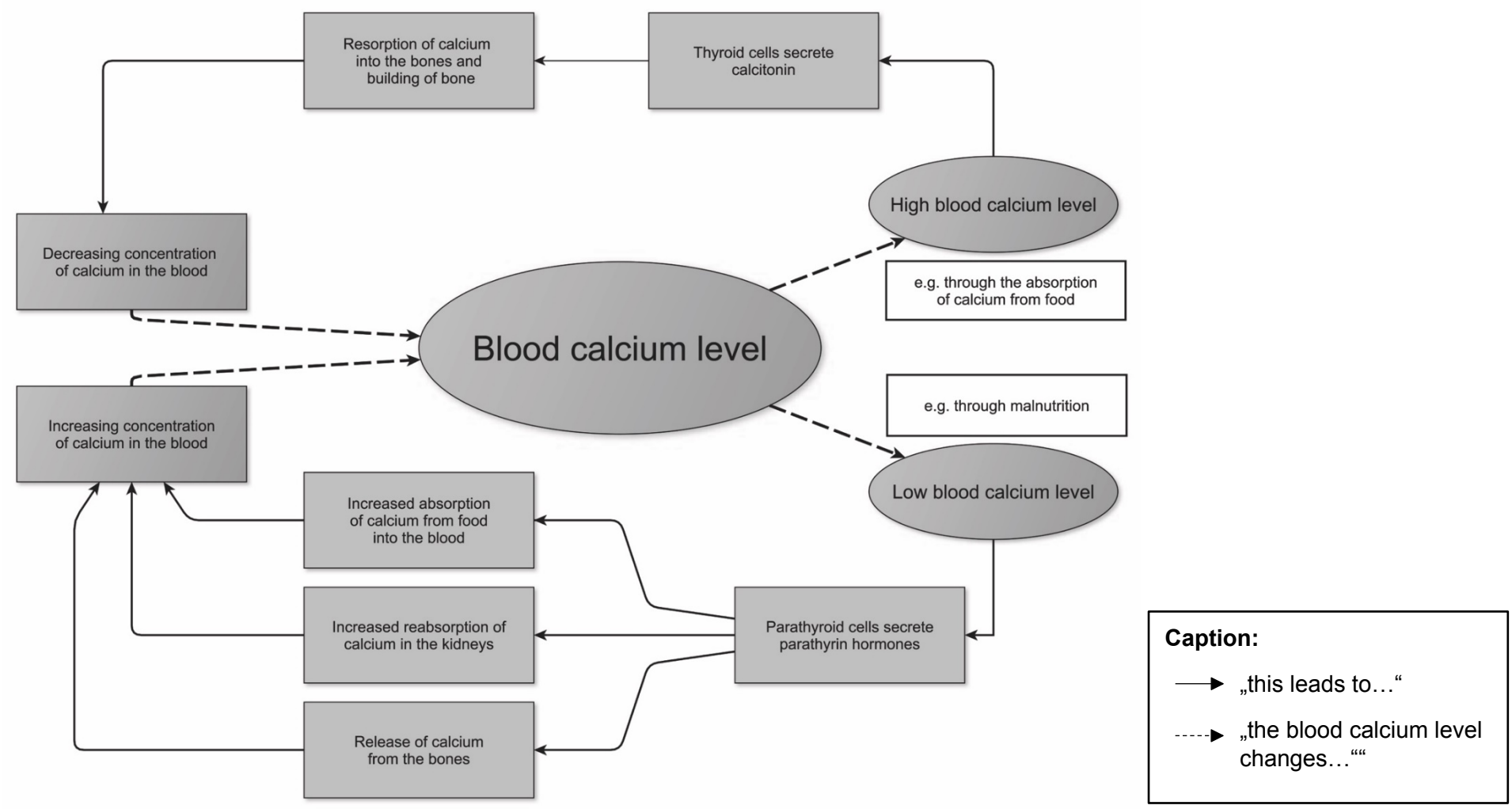
**Supplemental Material 1 – Causal Loop Diagram (Translation from Original Language)**

**Figure X.**

*A causal loop diagram was used to illustrate the mechanisms of blood calcium control in the human body.*



**Supplemental Material 2 – Informational Text (Translation from Original Language)**

## Regulation of blood calcium levels

Calcium is an essential mineral in the human body: it is necessary, for example, for muscle tension and the formation of bones and teeth. Calcium must be absorbed through the food. A lot of calcium is contained in dairy products, cabbage and legumes. Calcium can be absorbed into the blood from partly digested food in the intestine. With blood flow, calcium reaches all areas of the body. Calcium can be reabsorbed in the kidneys before it is excreted in urine.

Most of the calcium in the human body is stored in the bones. Only a very small part can be found in the blood. The amount of calcium present in one unit of blood volume is called the calcium level. The calcium level in the blood is maintained between 10 and 12 mg of calcium in 100 mL of blood. Maintaining the blood calcium level within a limited range (i.e., maintaining the set point) ensures that all cells are sufficiently supplied with calcium. This biological phenomenon is called the regulation of calcium levels in the blood. If calcium levels in the blood are too low, there is a risk that muscle tension will be disturbed, and painful muscle spasms will occur. High calcium levels in the blood can lead to nervous system disorders.

Different mechanisms for maintaining blood calcium levels are controlled by hormones. Hormones are messenger substances that are produced in glands and distributed throughout the bloodstream. They affect distant tissues by binding to receptors in the corresponding cells, resulting in a change in cell function. The thyroid and parathyroid glands are particularly important for the regulation of calcium levels. Calcitonin and parathyrin hormones are produced in the thyroid and parathyroid glands.

## Supplemental Material 3 – Assessment Tasks (Translation from Original Language)

### Task Format 1 (True-False Format)

| No. | Statements | The statement is correct. | The statement is not correct. |
|---|---|---|---|
| so1 | The **level of calcium in the blood** affects the **amount of calcium in the diet**. | ☐ | ☐ |
| | The **amount of calcium in the diet** affects the **level of calcium in the blood**. | ☐ | ☐ |
| so2 | The **amount of calcium in the diet** affects the **hormone concentration of calcitonin** in the blood. | ☐ | ☐ |
| | The **hormone concentration of calcitonin** in the blood affects the **amount of calcium in the diet**. | ☐ | ☐ |
| so3 | The **hormone concentration of parathyrin** in the blood affects the **amount of calcium in the diet**. | ☐ | ☐ |
| | The **amount of calcium in the diet** affects the **hormone concentration of parathyrin** in the blood. | ☐ | ☐ |
| so4 | The **level of calcium in the blood** affects the **hormone concentration of parathyrin** in the blood. | ☐ | ☐ |
| | The **hormone concentration of parathyrin** in the blood affects the **calcium level in the blood**. | ☐ | ☐ |
| so5 | The **hormone concentration of calcitonin** in the blood affects the **calcium level in the blood**. | ☐ | ☐ |
| | The **level of calcium in the blood** affects the **hormone concentration of calcitonin** in the blood. | ☐ | ☐ |
| so6 | The **hormone concentration of calcitonin** in the blood affects the **hormone concentration of parathyrin** in the blood. | ☐ | ☐ |
| | The **hormone concentration of parathyrin** in the blood affects the **hormone concentration of calcitonin** in the blood. | ☐ | ☐ |

### Task Format 2.1 (Two-Tier Format) for System Behavior

sb1.1

Imagine the following **situation**: An **increased release of parathyrin into the blood.**

This scenario has the following **consequences** on the **process of calcium release from the bones.** Select an appropriate justification.

- ☐ The process of calcium release from the bones **increases**.
- ☐ The process of calcium release from the bones **decreases**.

Justification:

- ☐ The presence of parathyrin in the blood **leads to** an **increased** release of calcium from the bones.
- ☐ The presence of parathyrin in the blood **leads to** a **decreased** release of calcium from the bones.
- ☐ The following trigger **causes** the presence of parathyrin in the blood: an **increased** release of calcium from the bones.
- ☐ The following trigger **causes** the presence of parathyrin in the blood: a **decreased** release of calcium from the bones.

sb1.2

Imagine the following **situation**: **Calcium** is **increasingly incorporated into bones.**

This scenario has the following **consequences** on the **level of calcium in the blood**. Select an appropriate justification.

- ☐ The level of calcium in the blood **increases**.
- ☐ The level of calcium in the blood **decreases**.

Justification:

- ☐ Increased incorporation of calcium into bones **leads to** an **increased** level of calcium in the blood.
- ☐ Increased incorporation of calcium into bones **leads to** a **decreased** level of calcium in the blood.
- ☐ The following trigger **causes** increased incorporation of calcium into bones: an **increased** level of calcium in the blood.
- ☐ The following trigger **causes** increased incorporation of calcium into bones: a **decreased** level of calcium in the blood.

sb1.3

Imagine the following **situation**: **Calcitonin** is **not/only in small amounts released into the blood**.

This scenario has the following **consequences** on the **process of calcium incorporation into bones.** Select an appropriate justification.

- ☐ The process of calcium incorporation into bones **increases**.
- ☐ The process of calcium incorporation into bones **decreases**.

Justification:

- ☐ The presence of calcitonin in the blood **leads to** an **increased** incorporation of calcium into bones.
- ☐ The presence of calcitonin in the blood **leads to** a **decreased** incorporation of calcium into bones.
- ☐ The following trigger **causes** the presence of calcitonin in the blood: **increased** incorporation of calcium into bones.
- ☐ The following trigger **causes** the presence of calcitonin in the blood: **decreased** incorporation of calcium into bones.

sb1.4

Imagine the following **situation**: Calcium is **not/only in small amounts absorbed from the diet into the blood.**

This scenario has the following **consequences** on the **level of calcium in the blood.** Select an appropriate justification.

- ☐ The level of calcium in the blood **increases**.
- ☐ The level of calcium in the blood **decreases**.

Justification:

- ☐ Increased absorption of calcium from the diet into blood **leads to** an **increased** level of calcium in the blood.
- ☐ Increased absorption of calcium from the diet into blood **leads to** a **decreased** level of calcium in the blood.
- ☐ The following trigger **causes** increased absorption of calcium from the diet into blood: an **increased** level of calcium in the blood.
- ☐ The following trigger **causes** increased absorption of calcium from the diet into blood: a **decreased** level of calcium in the blood.

sb1.5

Imagine the following **situation**: The blood calcium level decreases below the target value as a result of **increased incorporation of calcium into bones.**

This scenario has the following **consequences** on the **process of parathyrin release into the blood**. Select an appropriate justification.

- ☐ The process of parathyrin release **increases**.
- ☐ The process of parathyrin release **decreases**.

Justification:

- ☐ A decrease in the calcium level in the blood below the target value due to increased incorporation of calcium into bones **leads to** an **increased** release of parathyrin.
- ☐ A decrease in the calcium level in the blood below the target value due to increased incorporation of calcium into bones **leads to** a **decreased** release of parathyrin.
- ☐ The following trigger **causes** an increased incorporation of calcium into bones and a **decreased** calcium level in the blood below the target value: an **increased** release of parathyrin.
- ☐ The following trigger **causes** increased an incorporation of calcium into bones and a **decreased** calcium level in the blood below the target value: a **decreased** release of parathyrin.

sb1.6

Imagine the following **situation**: As a result of **the increased incorporation of calcium into bones**, the calcium level in the blood decreases below the target value.

This scenario has the following **consequences** on the **process of calcitonin release into the blood**. Select an appropriate justification.

- ☐ The process of calcitonin release into the blood **increases**.
- ☐ The process of calcitonin release into the blood **decreases**.

Justification:

- ☐ A decrease in the calcium level in the blood below the target value due to increased incorporation of calcium into bones **leads to** an **increased** release of calcitonin.
- ☐ A decrease in the calcium level in the blood below the target value due to increased incorporation of calcium into bones **leads to** a **decreased** release of calcitonin.
- ☐ The following trigger **causes** an increased incorporation of calcium into bones and a decrease in the calcium level in the blood below the target value: an **increased** release of calcitonin.
- ☐ The following trigger **causes** an increased incorporation of calcium into bones and a decrease in the calcium level in the blood below the target value: a **decreased** release of calcitonin.

sb1.7

Imagine the following **situation**: The level of calcium in the blood decreases below the target value as a result of **no/low reabsorption of calcium in the kidneys**.

This scenario has the following **consequences** on the **release of calcium from the bones**. Select an appropriate justification.

- ☐ The process of releasing calcium from the bones **increases**.
- ☐ The process of releasing calcium from the bones **decreases**.

Justification:

- ☐ An increase in the calcium level in the blood above the target value **due** to increased reabsorption of calcium in the kidneys **leads to** an **increased** release of calcium from the bones.
- ☐ An increase in the calcium level in the blood above the target value **due** to increased reabsorption of calcium in the kidneys **leads to** a **decreased** release of calcium from the bones.
- ☐ The following trigger **causes** an increased reabsorption of calcium in the kidneys and an **increased** calcium level in the blood above the target value: an **increased** release of calcium from the bones.
- ☐ The following trigger **causes** an increased reabsorption of calcium in the kidneys and an **increased** calcium level in the blood above the target value: a **decreased** release of calcium from the bones.

sb1.8

Imagine the following **situation**: The blood calcium level decreases below the target value as a result of **no/low release of calcium from the bones.**

This scenario has the following **consequences** on the **process of calcium incorporation into bones**. Select an appropriate justification.

- ☐ The process of calcium incorporation into bones **increases**.
- ☐ The process of calcium incorporation into bones **decreases**.

Justification:

- ☐ An increase in the calcium level in the blood above the target value **due** to an increased release of calcium from the bones **leads to** an **increased** incorporation of calcium into bones.
- ☐ An increase in the calcium level in the blood above the target value **due** to an increased release of calcium from the bones **leads to** a **decreased** incorporation of calcium into bones.
- ☐ The following trigger **causes** an increased release of calcium from the bones an **increased** calcium level in the blood above the target value: an **increased** incorporation of calcium into bones.
- ☐ The following trigger **causes** an increased release of calcium from the bones and an **increased** calcium level in the blood above the target value: a **decreased** incorporation of calcium into bones.

### Task Format 2.1 (Two-Tier Format) for Regulative Measures

rm1.1

Imagine the following **aim**: **Calcium** should be **increasingly incorporated into bones.**

This condition can be triggered by the following **modification** in the process of **calcitonin release** into the blood. Select an appropriate justification.

- ☐ By an **increased** release of calcitonin into the blood.
- ☐ By a **decreased** release of calcitonin into the blood.

Justification:

- ☐ Increased incorporation of calcium into bones **leads to increased** release of calcitonin into the blood.
- ☐ Increased incorporation of calcium into bones **leads to decreased** release of calcitonin into the blood
- ☐ The following trigger **causes** increased incorporation of calcium into bones: an **increased** release of calcitonin.
- ☐ The following trigger **causes** increased incorporation of calcium into bones: a **decreased** release of calcitonin.

rm1.2

Imagine the following **aim**: **Calcium** should be **increasingly reabsorbed in the kidneys**.

This condition can be triggered by the following **modification** in the process of **releasing parathyrin** into the blood. Select an appropriate justification.

- ☐ By an **increased** release of parathyrin into the blood.
- ☐ By a **decreased** release of parathyrin into the blood.

Justification:

- ☐ Increased reabsorption of calcium in the kidneys **leads to** an **increased** release of parathyrin.
- ☐ Increased reabsorption of calcium in the kidneys **leads to** a **decreased** release of parathyrin.
- ☐ The following trigger **causes** increased reabsorption of calcium in the kidneys: an **increased** release of parathyrin.
- ☐ The following trigger **causes** increased reabsorption of calcium in the kidneys: a **decreased** release of parathyrin.

rm1.3

Imagine the following **aim:** Calcium should **not** be **released**/only **released in small amounts** from the bones.

This condition can be triggered by the following **modification** in the process of **releasing parathyrin** into the blood. Select an appropriate justification.

- ☐ By an **increased** release of parathyrin into the blood.
- ☐ By a **decreased** release of parathyrin into the blood.

Justification:

- ☐ An increased release of calcium from bones **leads to** an **increased** release of parathyrin.
- ☐ An increased release of calcium from bones **leads to** a **decreased** release of parathyrin.
- ☐ The following trigger **causes** an increased release of calcium from the bones: an **increased** release of parathyrin.
- ☐ The following trigger **causes** an increased release of calcium from the bones: a **decreased** release of parathyrin.

rm1.4

Imagine the following **aim**: The **level of calcium in the blood** should **increase**.

This condition can be triggered by the following **modification** in the process of **incorporation of calcium into the bones.** Select an appropriate justification.

- ☐ By an **increased** incorporation of calcium into the bones.
- ☐ By a **decreased** incorporation of calcium into the bones.

Justification:

- ☐ A decreased level of calcium in the blood **leads to increased** incorporation of calcium into the bones.
- ☐ A decreased level of calcium in the blood **leads to decreased** incorporation of calcium into the bones.

- ☐ The following trigger **causes** a decreased level of calcium in the blood: **increased** incorporation of calcium into the bones.
- ☐ The following trigger **causes** a decreased level of calcium in the blood: **decreased** incorporation of calcium into the bones.

rm1.5

Imagine the following **aim**: **Calcitonin** should be **increasingly released** into the blood.

This condition can be triggered by the following **modification** in the process of **calcium incorporation into the bones.** Select an appropriate justification.

- ☐ **Increased** incorporation of calcium into the bones, causing the blood calcium level to **decrease** below the target value.
- ☐ **Decreased** incorporation of calcium into the bones, causing the blood calcium level to **increase** above the target value.

Justification:

- ☐ An increased release of calcitonin **leads to increased** incorporation of calcium into the bones and an increase in the calcium level in the blood above the target value.
- ☐ An increased release of calcitonin **leads to decreased** incorporation of calcium into the bones and an increase in the calcium level in the blood above the target value.
- ☐ The following trigger **causes** an increased release of calcitonin: an **increased** incorporation of calcium into the bones resulting in an increased calcium level in the blood above the target value**.**
- ☐ The following trigger **causes** an increased release of calcitonin: a **decreased** incorporation of calcium into the bones resulting an increased calcium level in the blood above the target value**.**

rm1.6

Imagine the following **aim**: **Calcium** should be **increasingly incorporated into the bones**.

This condition can be triggered by the following **modification** in the process **of calcium reabsorption in the kidneys.** Select an appropriate justification.

- ☐ **Increased** calcium reabsorption in the kidneys, causing the blood calcium level to **increase** above the target value.
- ☐ **Decreased** calcium reabsorption in the kidneys, causing the blood calcium level to **decrease** below the target value.

Justification:

- ☐ Increased calcium incorporation into bones **leads to increased** calcium reabsorption in the kidneys and an increase in the calcium level in the blood above the target value.
- ☐ Increased calcium incorporation into bones **leads to decreased** calcium reabsorption in the kidneys and an increase in the calcium level in the blood above the target value.
- ☐ The following trigger **causes** increased incorporation of calcium into the bones: **increased** reabsorption of calcium in the kidneys resulting in an increased calcium level in the blood above the target value.
- ☐ The following trigger **causes** increased incorporation of calcium into the bones: **decreased** reabsorption of calcium in the kidneys resulting in an increased calcium level in the blood above the target value.

rm1.7

Imagine the following **aim**: Calcitonin should **not** be **released into the blood**/only be **released into the blood in small amounts**.

This condition can be triggered by the following **modification** in the process of **calcium release from the bones.** Select an appropriate justification.

- ☐ **Increased** release of calcium from the bones, causing the blood calcium level to **increase** above the target value.
- ☐ **Decreased** release of calcium from the bones, causing the blood calcium level to **decrease** below the target value.

Justification:

- ☐ The presence of calcitonin in the blood **leads to** an **increased** release of calcium from the bones and an increase in the calcium level in the blood above the target value.
- ☐ The presence of calcitonin in the blood **leads to** a **decreased** release of calcium from the bones and an increase in the calcium level in the blood above the target value.
- ☐ The following trigger **causes** the presence of calcitonin: an **increased** release of calcium from the bones resulting in an increased calcium level in the blood above the target value.
- ☐ The following trigger **causes** the presence of calcitonin: a **decreased** release of calcium from the bones resulting in an increased calcium level in the blood above the target value.

rm1.8

Imagine the following **aim**: Parathyrin should **not** be **released/** only be **released into the blood in small amounts**.

This condition can be triggered by the following **modification** in the process of **releasing calcium from the bones.** Select an appropriate justification.

- ☐ **Increased** release of calcium from bones, causing the blood calcium level to **increase** above the target value.
- ☐ **Decreased** release of calcium from bones, causing the blood calcium level to **decrease** below the target value.

Justification:

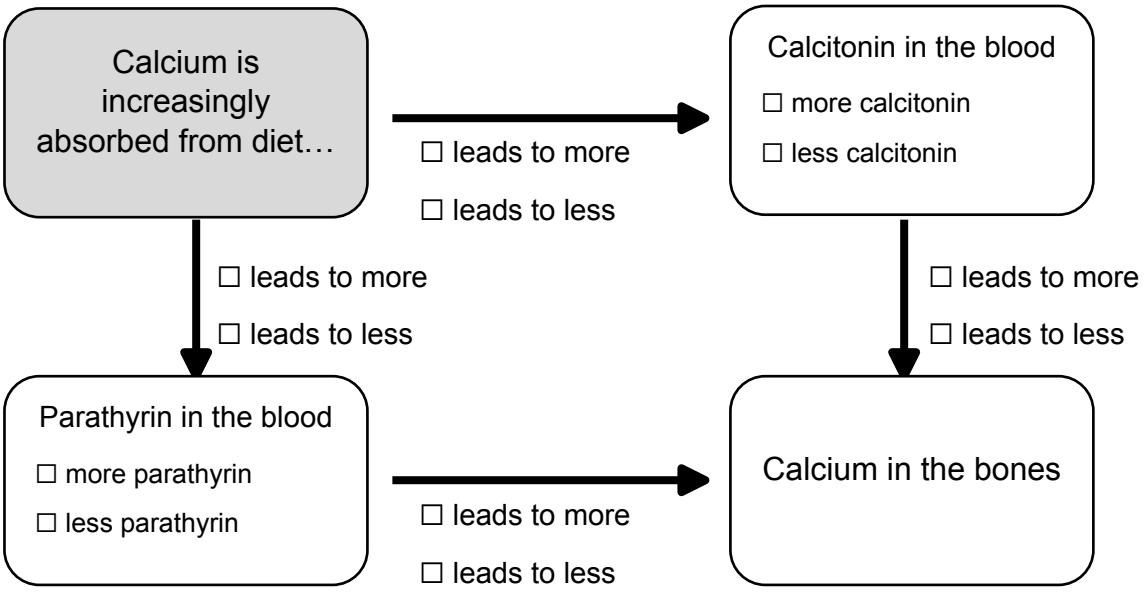
- ☐ The presence of parathyrin in the blood **leads to** an **increased** release of calcium from the bones and a decrease in the calcium level in the blood below the target value.
- ☐ The presence of parathyrin in the blood **leads to** a **decreased** release of calcium from the bones and a decrease in the calcium level in the blood below the target value.
- ☐ The following trigger **causes** the presence of parathyrin: an **increased** release of calcium from the bones resulting in a decreased calcium level in the blood below the target value.
- ☐ The following trigger **causes** the presence of parathyrin: a **decreased** release of calcium from the bones resulting in a decreased calcium level in the blood below the target value.

### Task Format 2.2 (Multiple-Choice Concept Map Format) for System Behavior

sb2.1 and sb2.2

Imagine the following **situation**: **Calcium is increasingly absorbed from food into the blood.**

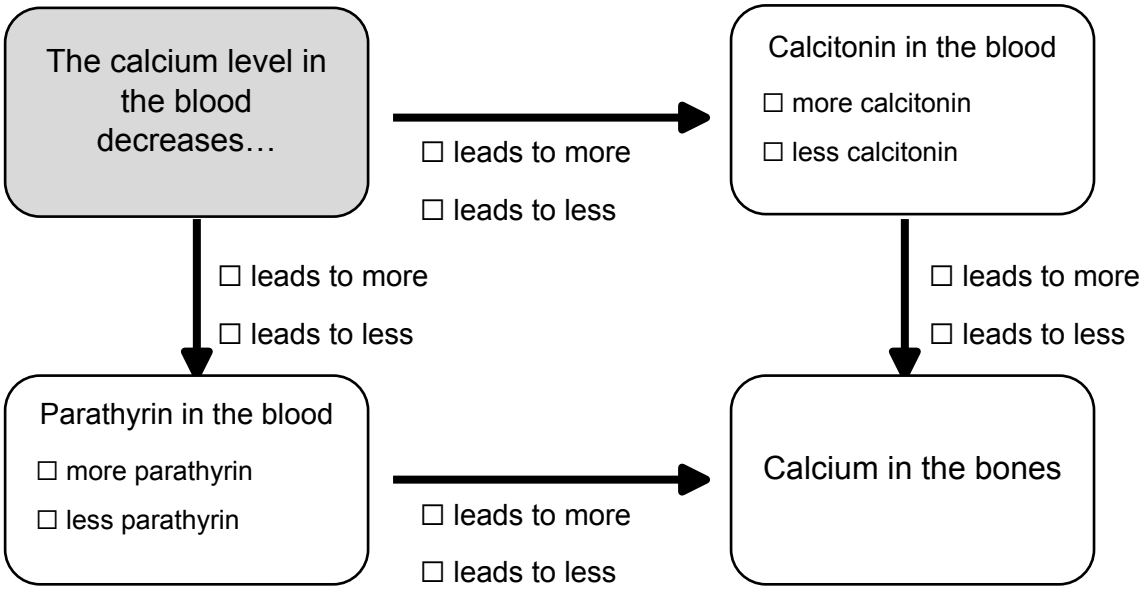
For each pair of statements, tick the answer option reflecting the **impact of this change** on the elements shown.




sb2.3 and sb2.4

Imagine the following **situation**: **The calcium level in the blood decreases.**

For each pair of statements, tick the answer option reflecting the **impact of this change** on the elements shown.

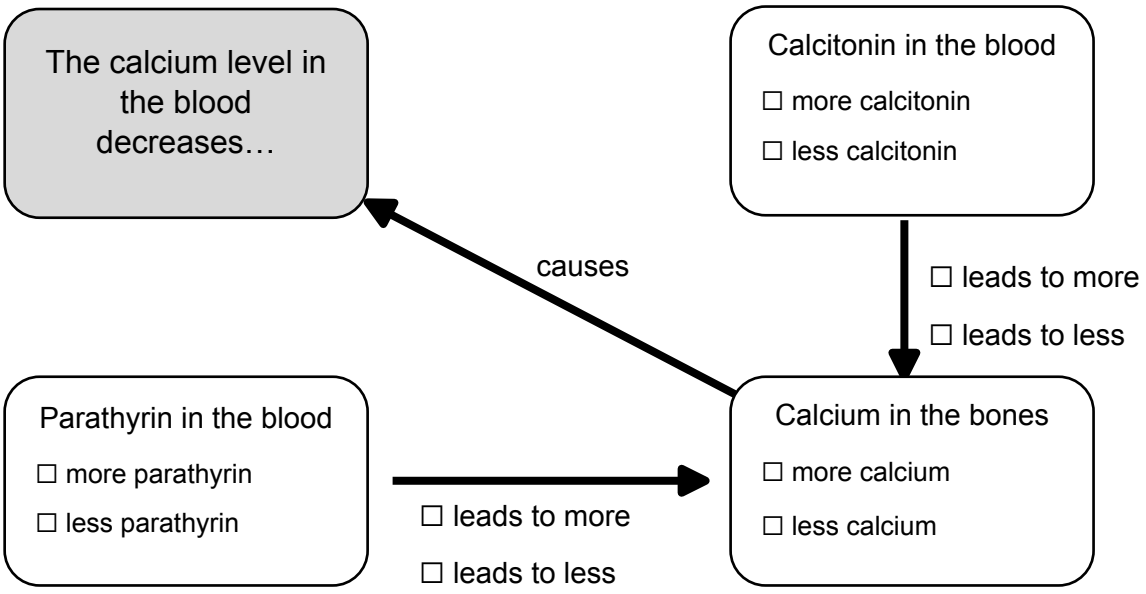


### Task Format 2.2 (Multiple-Choice Concept Map Format) for Regulative Measures

rm2.1 and rm2.2

Imagine the following **aim**: **The calcium level in the blood should decrease.**

For each pair of statements, tick which of the answer options represent **the changes required** to achieve the given aim.




rm2.3 and rm2.4

Imagine the following **aim**: **The calcium level in the blood should increase.**

For each pair of statements, tick which of the answer options represent **the changes required** to achieve the given aim.

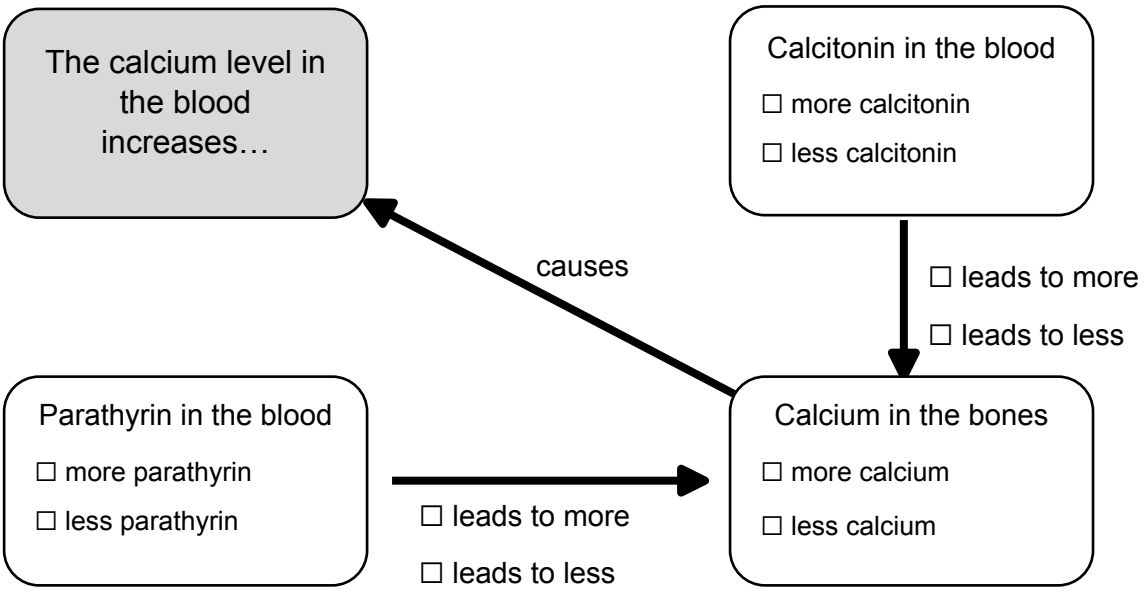


**Table X.**

*Item Parameter Estimates for 1D and 3D Model*

| | 1D | | 3D | |
|---|---|---|---|---|
| Item | Estimate | Infit | Estimate | Infit |
| so1 | -2.08 | 0.98 | -2.07 | 0.95 |
| so2 | -1.68 | 1.05 | -1.65 | 0.96 |
| so3 | -1.09 | 1.18 | -1.06 | 1.06 |
| so4 | -0.57 | 1.01 | -0.54 | 0.93 |
| so5 | -0.39 | 1.02 | -0.36 | 0.91 |
| so6 | 1.70 | 1.31 | 1.71 | 1.18 |
| sb1.1 | -1.21 | 0.97 | -1.18 | 0.93 |
| sb1.2 | -1.43 | 1.01 | -1.40 | 0.99 |
| sb1.3 | -0.04 | 0.93 | -0.03 | 0.92 |
| sb1.4 | -0.11 | 1.01 | -0.09 | 0.98 |
| sb1.5 | -0.60 | 0.96 | -0.58 | 0.94 |
| sb1.6 | 0.24 | 1.06 | 0.25 | 1.05 |
| sb1.7 | 1.92 | 1.04 | 1.92 | 1.04 |
| sb1.8 | 1.96 | 1.14 | 1.96 | 1.11 |
| sb2.2 | -1.25 | 1.11 | -1.22 | 1.04 |
| sb2.3 | -0.34 | 1.00 | -0.33 | 0.97 |
| sb2.1 | 0.20 | 1.00 | 0.21 | 0.97 |
| sb2.4 | -0.32 | 1.01 | -0.30 | 1.05 |
| rm1.1 | -0.99 | 0.84 | -1.10 | 0.90 |
| rm1.2 | -1.05 | 0.90 | -1.15 | 0.97 |
| rm1.3 | 0.04 | 0.83 | 0.07 | 0.86 |
| rm1.4 | 0.70 | 0.95 | 0.82 | 1.04 |
| rm1.5 | 0.42 | 0.97 | 0.49 | 1.05 |
| rm1.6 | -0.42 | 1.04 | -0.45 | 1.16 |
| rm1.7 | 0.37 | 0.91 | 0.44 | 0.99 |
| rm1.8 | 0.61 | 0.97 | 0.71 | 1.09 |
| rm2.2 | 0.56 | 0.90 | -0.34 | 0.93 |
| rm2.3 | 0.44 | 0.96 | 0.38 | 1.04 |
| rm2.1 | 0.45 | 0.96 | 0.35 | 1.02 |
| rm2.4 | 0.44 | 0.91 | 0.41 | 0.94 |

## Additional Comparisons of One- and Multidimensional Models

**Table X.**

*Comparison of One- (#1), Two- (#2.1, 2.2, 2.3), and Three- (#3) Dimensional Models of Feedback Loop Reasoning by Means of Statistical Information Criteria. For Inferential Statistics see Text.*

| Model | *N* Dim | Skills | *N* Items | Dev | *N* Par | AIC | BIC |
|---|---|---|---|---|---|---|---|
| 1 | 1 | One general skill | 30 | 6781 | 31 | 6843 | 6947 |
| 2.1 | 2 | O<br>SB + RM | 6<br>24 | 6739 | 33 | 6805 | 6916 |
| 2.2 | 2 | O + SB<br>RM | 18<br>12 | 6736 | 33 | 6802 | 6913 |
| 2.3 | 2 | O + RM<br>SB | 18<br>12 | 6766 | 33 | 6832 | 6943 |
| 3 | 3 | O<br>SB<br>RM | 6<br>12<br>12 | 6711 | 36 | 6783 | 6904 |

*Note. N* Dim, number of dimensions; *N* Items, number of items; Dev, deviance; *N* Par, number of parameters; AIC, Akaike information criterion; BIC, Bayesian information criterion; SO, System Organization; SB, System Behavior; RM, Regulative Measures.

### Likelihood Ratio Tests

model 1 vs. model 2.1 $\chi^2(2) = 41.4$, $p < .001$

model 1 vs. model 2.2 $\chi^2(2) = 44.8$, $p < .001$;

model 2.1 vs. model 3: $\chi^2(3) = 28.2$, $p < .001$;

model 2.2 vs. model 3: $\chi^2(3) = 24.8$, $p < .001$