Creating Assessment Questions for Systems Thinking Concepts

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We measure what we care about (Meadows, et al, 1972).

Abstract:

In this paper we undertake an effort to increase the collection of systems thinking assessment questions available to educators and researchers focused on the pre-college and undergraduate level of instruction. The first part of the paper lists a hierarchical set of systems thinking concepts that lend themselves to assessment through questions, followed by some examples of systems thinking assessment questions at each level. The second part of the paper presents some guidelines for developing concept inventories. It is the hope that systems thinking inventories at the primary school, middle school, and secondary school level will be developed in an effort to support the infusion of more systems thinking concepts in education for students ages 5 to 22. It is the intention to make the list of systems thinking assessment questions freely available through the Creative Learning Exchange. The research and analysis needed to develop systems thinking concept inventories is a second stage for this effort.

Introduction

As we face daunting problems, dealing with global pandemics, economies degraded by shuttering businesses to reduce the spread of disease, loss of educational opportunities for millions of children as we try to protect students and teachers from disease exposure, increase in poverty as families try to find scarce jobs, decrease in mental health due to social isolation, we must increase our effort to look at problems from a systemic perspective. The current pandemic is an immediate, and relatively short-term problem, but the United Nations (2019), taking a long-term view of global, systemic problems indicates that "students need education in mathematics and natural sciences, learning to write and communicate persuasively, cooperate in teams and acquire leadership and *systems thinking*" [italics added] to "understand the processes that maintain healthy functioning of the Earth system and sustain life (p. 49)." Systems thinking concepts continue to make their way, formally, into the disciplines of science, medicine, business, engineering, and social science, among others. We find, more and more often, wisdom in Sterman's (2002) words, "there are no side effects – only effects." Donella Meadows (2008) wrote extensively about the importance of systems thinking in our lives. "The systems-thinking lens allows us to reclaim our intuition about whole systems … then we can use our insights to make a difference in ourselves and our world." She continues, "…if we want to bring about the thoroughgoing restructuring of systems that is necessary to solve the world's gravest problems – poverty, pollution, and war – the first step is *thinking differently*" (Meadows, 1991). For her, thinking differently is accomplished by developing (and applying) our systems thinking skills and our ability to use system dynamics modeling.

The Next Generation Science Standards in the U.S. explicitly states as one of six cross-cutting science goals that students need to understand *systems and system modeling*. Yoon, et al (2018) indicate that the concept of systems has played significant role in "driving science learning in U.S.

K-12 education." Reviewing other national U.S. national education standards in middle and secondary school mathematics, science, social science, health, economics, and education in general one finds multiple standards that directly relate to the need for students to think systemically (Fisher, et al, 2019).

Yet there are no formal assessment questions available to the educators who hope to increase student understanding of core systems thinking (ST) concepts. How are educators to assess student understanding of ST concepts without a bank of appropriate questions to use in their classes? Moreover, if we are to increase the research around documenting the value of the infusion of ST concepts in instruction those researchers need quality ST assessment questions to use in their analysis. Members of the system dynamics society (SDS) are in a pivotal position to lead research in providing a guiding set of ST concepts appropriate for inclusion in instruction and research and in providing an initial collection of ST assessment questions to help fill this gap. A group of SDS educators and researchers and other colleagues have begun an effort to remedy this deficiency.

This paper is divided into two sections. The first section describes one hierarchical set of levels of systems thinking concepts that lend themselves to being assessed by specific questions. Each level of systems thinking concepts is then followed by a short table that displays a subset of example assessment questions that could fall into that ST category. The second section discusses the development of concept inventories. Concept inventories are used in various science and mathematics disciplines to assess foundation concepts for a given subject (CEI, 2021). It is our goal to develop such concept inventories for ST at the primary school, middle school, and secondary school levels.

Part 1: Collecting Assessment Questions

The design of appropriate/useful assessment questions for evaluating systems thinking skill has been woefully neglected in the SDS. No doubt the reason is that there are no assessment experts within the society. As we wait to have someone with appropriate expertise guide us I believe we can collect those questions that many of us have used over the years to assess the understanding of our students as we endeavor to increase their knowledge of systemic dynamics and systems thinking.

This collection can be a valuable asset to educators who are trying to introduce ST in their instruction and to those of us who would like a broader variety of ST questions to use both in instructional and research settings. Hopefully this initial set of ST assessment questions will be improved and enhanced both in quality and quantity over time.

It is the intention of the authors to focus on students ages 5 to 22. To truly make ST a core method of analysis for future generations we must start in pre-college (Forrester, 2007). We have found that many questions intended for secondary school students have worked quite well for undergraduate students, so have extended the intended audience to include that age group as well.

While the ST assessment questions we collect will come from disparate disciplines, the core systems thinking concept being assessed in each question can often lend itself to being clothed in a scenario from another discipline; thus the collection of ST questions has the potential to be a seedbed.

To guide us in building this collection of ST assessment questions we can look to those research documents that have enumerated important ST concepts. An extremely useful list of ST concepts is contained in a table in the work of Hopper and Stave (2008). Forrester (2009) mentions the need for students to see interrelatedness, to surface their mental models, to recognize the impact of delays, to observe how policies can be applied in the wrong direction, and he stresses the importance of testing one's hypotheses using simulation. Kim (1999) mentions the importance of behavior over time graphs in displaying the dynamics of important variable in the system, using stock/flow and causal loops to represent a systemic problem, and how to identify reinforcing and balancing feedback. Meadows' (2008) entire book "Thinking in Systems" is replete with rich example of systems thinking concepts. Richmond (2001) describes the importance of dynamic closed-loop and non-linear thinking, surfacing mental models and making those mental models operational. Of course, Schaffernicht & Groesser (2016) identify the many concepts necessary to developing increasing skill in building system dynamics understanding. Their description of SD Language Skills and description of Dynamic Reasoning Skills were especially useful for the construction of the ST concepts in this paper. The Waters Center for Systems Thinking markets a deck of 14 ST cards that highlight different systems thinking concepts including identifying interrelationships between parts of a system, behavior over time graphs of important variables, impact of delays, etc.

Although many of the questions stated in this list are for older students, it is to be noted that almost all of the core ST Concepts are applicable to younger age groups. The questions could be modified for younger students with a different context or the same concept could be accessed by an entirely different question. This is far from a comprehensive list at this point.

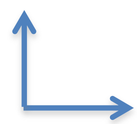
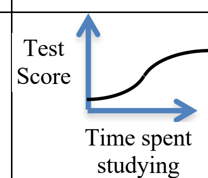
A Suggested List of Core ST Concepts That Lend Themselves to Assessment

Some sample questions for each category in the ST concepts hierarchical list are provided to give the reader a sense of what could be used to begin the collection we aim to compile.

Level 1: **Recognizing** the dynamic nature of systems

- Recognize dynamic, systemic problems (in stories or the news) ie. elements and interconnections for a purpose.
- Interpret correctly information displayed graphically.
- Identify parts of a system.
- Identify causal connections among parts.
    - Recognize chains of causal links.
- Explain/Sketch behavior over time of important elements in the system using words or graphs (including reference graphs).
- Recognize that a system is more than the sum of its parts.

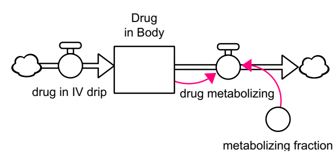
What is the ST concept?	**What is the purpose of the question**	**Question**	**Answer**	**Age group**

Recognizing the dynamic nature of systems	Identify parts of a system	Identify at least three parts of the system that produce a flower.	Possible choices: flower seed, sun, soil, water/rain, parent flower, nutrients, …	8-11
	Identify causal connection among parts	Draw a causal link between two of the following elements that show that one element causes the other element. Pigs, pig pen, trees, corn, cows, tractor, piglets	Pigs -> piglets Or Piglets -> pigs	8-11
	Identify causal connection among parts	For each of the next two questions (a and b) do the following: i. Complete the sentence to describe a causal relationship. ii. Draw an arrow connector to represent the causation. Example: Consumption of desserts causes a change in _weight_. Consumption of desserts → Weight a. Amount of exercise causes a change in ___. Exercise → ? b. Number of births causes a change in _____. Births → ?	Possible answers: a. exercise→ weight exercise → strength exercise → hunger b. births→ population births → food/person	12-16
	Describe a problem as behavior over time.	A student prepares for an examination. The more she prepares, the better her performance, up to a point, after which additional study does not improve her test score. Translate this relationship into a graph. (Use the axes shown above. No numbers are required on the axes, Just label each axis and sketch a graph.) Explain the reason for the shape of your graph. 	 As student starts to study few concepts recalled so score stays low. Longer study helps student recall more. Eventually most concepts studied and/or fatigue occurs, so diminishing returns.	12-16

Level 2: **Representing** the system with stocks and flows

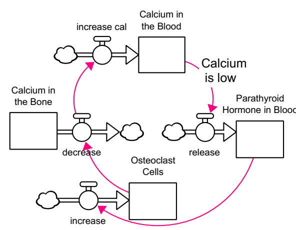
- Differentiating types of variables.
    - Distinguish system's variables as stocks, flows, other.
- Identify units of measure for stocks, flows, other variables.
- Sketch initial hybrid Stock/Flow-CLD diagram structure to capture important system components and interactions.
- Use an initial hybrid Stock/flow-CLD diagram structure as a communication tool to aid explanation about system structure (explain mental model).
- Understand that behavior is a function of structure ⇔ Infer basic structure from behavior.
    - Explain graphically, flow behavior given stock behavior.
    - Explain graphically, stock behavior given flow behavior.
    - Hand calculate stock<>flow values in simple models
- Explain Bathtub Dynamics (stock behavior based on inflow and outflow relative size; size and pattern).

- Identify closed loops.
- Capture the assumptions about the system from stakeholders and/or modelers.

What is the ST concept?	What is the purpose of the question	Question	Answer	Age group
Representing the system with stocks and flows	Distinguish types of variables	For the list of words below, place a **box** around those ideas that represent **accumulations** (increase/decrease over time) and underline those ideas that represent the rate at which a boxed value could change. a. diffusion b. drug in the body c. blood glucose d. insulin release e. synthesis f. elimination fraction g. osteoblasts h. decay	a. diffusion b. drug in the body c. blood glucose d. insulin release e. synthesis f. elimination fraction g. osteoblasts h. decay	17-22
	Sketch initial S/F diagram to capture important system components and interactions	Assume a patient enters the emergency room needing immediate treatment. A doctor decides to connect this patient to an IV drip to allow a constant amount of therapeutic drug to enter the patient's body. The drug will exit the body at a very small rate proportional to (a percentage of) the amount of drug in the body over time. Sketch the stock/flow diagram for this scenario if we are interested in tracking the amount of drug in the patient's body over time.		14-22
	Explain Bathtub Dynamics (stock behavior based on inflow and outflow relative size)	For the past ten years the frogs in a nearby ecosystem have had a larger number of deaths than births. What can we conclude about the total number of frogs in this ecosystem over the past ten years? a. The total number of frogs has increased. b. The total number of frogs has decreased. c. The total number of frogs has remained the same d. It is not possible to tell from the information given.	B	8-14

Level 3: **Identifying** Feedback

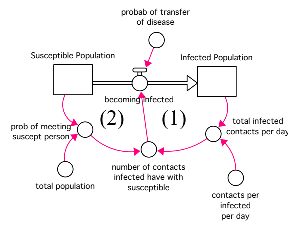
- Describe polarity of a link.
- Understand the difference between reinforcing and balancing feedback.
- Understand why no feedback is possible without at least one stock.
- Determine the polarity of a loop (reinforcing or balancing).
- Identify the feedback in a stock/flow diagram.
- Identify dominant feedback from a graph or dynamic variable over time.

What is the ST concept?	What is the purpose of the question	Question	Answer	Age group
Identifying Feedback	Identify polarity of a link.	For the causal links given below indicate the polarity (i.e., + or -) that an increase in the item on the left (source) causes for the change in the item on the right (effect). Example: Consumption of desserts causes a change in weight. Consumption of desserts —(+)→ weight a. exercise → weight exercise → strength exercise → hunger b. births → population births → food/person	Possible answers: a. exercise —(-)→ weight exercise —(+)→ strength exercise —(+)→ hunger b. births —(+)→ population births —(-)→ food/person	12-18
	Determine the polarity of a loop.	The following loop shows one of the feedback cycles for Calcium Homeostasis in the human body.  Circle the type of feedback represented: (Positive feedback, Negative Feedback). Explain why you chose the type of feedback you circled.	Negative (balancing) feedback. A decrease in calcium in the blood causes an increase in the release of parathyroid hormone which causes an increase in new osteoclast cells which causes more calcium to be released from bone into the blood, causing more new calcium in the blood.	17-22

Level 4: **Understanding** Dynamic Behavior

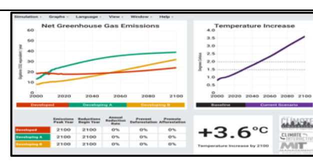
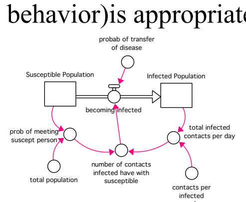
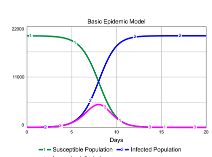
- Explain the behavior of a particular causal relationship, stock/flow diagram segment, or feedback loop
    - Explain/Identify the flow behavior that produces linear, exponential (growth/decay), convergent, oscillatory, overshoot and collapse patterns of stock over time.
    - Explain the effect of delays.
        - Recognize that oscillations require a delay in a balancing feedback loop.
- Explain the behavior of linked feedback loops.
- Explain the cause of transfer of loop dominance (that is, the model must contain non-linear defined components).
- Explain systemic behavior from different stakeholder perspectives.

What is the ST concept?	What is the purpose of the question	Question	Answer	Age group
Understanding Dynamic Behavior	Identify flow behavior needed to produce exponential pattern of	For a model with a single stock and single flow, the flow value for a stock that must increase (or decrease) exponentially should: a. Be a constant value	C	

	stock behavior	b. Increase (or decrease) in a linear fashion c. Be proportional to the stock value d. Be proportional to the growth (or decay) fraction		
	Explain the behavior of linked feedback loops	There are two feedback loops in this stock/flow diagram. Explain how the interaction of the two feedback loops can produce the typical s-shaped growth of the infected population over time. 	Feedback loop (1) is a reinforcing feedback loop that is dominant at the beginning of the simulation and so produces exponential growth of the Infected Population at the beginning of an epidemic. As the Susceptible Population stock becomes depleted (due to people becoming infected), feedback loop (2) which is a balancing loop becomes stronger eventually balancing the strength of the reinforcing loop. This leads to a steady state dynamic.	15-22

Level 5: **Using** Conceptual Models

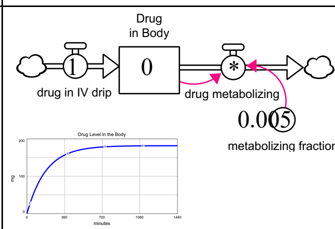
- Recognize transference of structure to other relevant scenarios.
  - Recognize archetypal behavior.
- Use a pre-constructed simulation to suggest potential solutions to a problem.
- Use a conceptual model sketch of a system (hybrid stock/flow-CLD diagram) structure to suggest potential solutions to a problem.

What is the ST concept?	**What is the purpose of the question**	**Question**	**Answer**	**Age group**
Using conceptual models	Use a pre-constructed simulation to suggest potential solutions to a problem	Use the C-Roads simulation with 3 country groups to determine reduction in greenhouse gasses to control increase in global temperature (≤ 2° C) over the next 80 years. 	A variety of solutions could be possible	16-22
	Recognize transference of structure to other relevant scenarios	Identify at least one other scenario in which the basic epidemic model structure (and behavior)is appropriate.  	1. Marketing a new product has potential buyers (susceptible) and those people who have purchased and like the new product (infected). 2. Spreading a rumor has those who have not heard the rumor	14-22

			(susceptible) and those who have heard it (infected)	

Level 6: **Creating** Simulation Models

- Represent relationships between variables in mathematical terms.
- Make sure the model has consistent units.
- Can build a dimensionless multiplier, when needed.
- Recognize the iterative nature of building a simulation model.
- Build an operational stock/flow model, and/or correctly append a functioning model segment to a core operational model.
- Operate the model.
- Validate the model.
- Recognize unintended consequence in model output.

What is the ST concept?	**What is the purpose of the question**	**Question**	**Answer**	**Age group**
Creating simulation models	Build an operational stock/flow model.	Assume you have sketched the stock/flow drug model from category 2 correctly. Assume the IV drip is delivering 1 mg of drug per minute and the patient is metabolizing the drug at 0.5% per minute. Operationalize this model. Anticipate the level of drug in the body over 24 hours. Display the model output for the drug in the body over 24 hours. Explain any discrepancy between your prediction and model output.		14-22
	Make sure a model has consistent units	Identify the correct units for the previous drug model.	Drug in Body = mg Drug in IV drip = mg/minute Drug metabolizing = mg/min Metabolizing fraction= 1/min	14-22

Level 7: **Testing** Policy

- Hypothesize the effect of changes in the model.
- Use a stock/flow simulation (whose structure you can alter) to test the effect of changes.
- Interpret model output with respect to a problem.
- Understand how to use model output to make real-world recommendations ⇔Use the model to identify places to intervene within the system.
- Design policies based on model analysis. Modify stock/flow structure as needed.
- Recognize policy resistance.

What is the ST concept?	What is the purpose of the question	Question	Answer	Age group
Testing policies	Hypothesize the effect of changes in the model. Use model to test the effect of changes. Use model to identify places to intervene within the system.	Assume you have a working drug model from the previous category. Assume one of the patient's kidneys quits working half-way through the simulation. What will happen to the drug level in the body? How will you correct the problem?	If one kidney fails the metabolizing fraction will be cut in half, which means the drug level will rise. To return the patient to the desired drug level reduce the IV drip. There are many potential scenarios that will work for modifying the IV drip rate.	14-22
	Use model to test the effect of changes. Understand how to use model output to make real world recommendation. Design policies based on model analysis.	Using the Fish Banks model that contains a fish segment and a boats catching fish segment, the simulation generally causes the fish population to collapse because too many boats are eventually built, catching too many fish. Determine which of the suggested policies would be most effective in stabilizing the fish population: a. Placing a tax on fish caught. b. Placing a tax on boats sent out to fish. c. Allowing boats to be scrapped after x years. d. Placing a limit on number of fish each boat can catch. e. Restricting technology that can locate fish.	C. The real problem is that there are too many fishing boats over time, so scrapping fishing boats tends to have the most immediate effect on reducing the number of fishing boats, as it is the only option that provides an outflow for fishing boats. All the other options just reduce the inflow.	14-22

Part II: Creating Systems Thinking Concept Inventories

Concept inventories are sets of assessment questions (usually in multiple choice format) that center around core concepts in a particular discipline. The questions are field tested to determine if, in fact, they do capture whether the student understands the concepts for which the inventory was created. The inventories are assessed for validity (they measure what they claim to measure) and reliability. Having such an inventory allows educators and researchers an opportunity to measure a "gain in learning" if equivalent subsets of concept inventory questions are used at various points in an educational setting (Sands, et al, 2018).

Another important component when constructing questions that make up the concept inventory is to use typical student misconceptions as distractors in the question formulation (Sands, et al, 2018). So it is important to communicate with educators who regularly assess the content in the concept inventory to determine typical misconceptions about concepts assessed in the inventory.

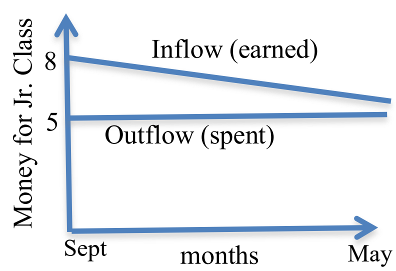
The suggested list of ST concepts identified above is only a beginning of what is hoped will become a more consensual collection of ST concepts. Once the list of ST concepts becomes more complete the next step will be to rate the difficulty and importance of each concept for each of the 3 levels (primary school, middle school, and secondary school) to which the concepts will be measured. (It is expected there will be a great deal of overlap in concept topic for each grade level, but less overlap in assignment of difficult of the concept for a given grade level.) Next it will be necessary to find the average difficulty and average importance of the ranked concepts. Those concepts that rank higher than average will be selected for concept inventory development (Sachan, et al, 2019).

Not only do we need a list of systems thinking concepts to provide a "target" for our assessment questions, we need some guidance about how to create certain types of assessment questions. Most notably, there are some very useful guidelines for developing multiple choice questions. See Appendix 1 for a list of guiding principles for creating multiple choice questions (Eberly Center, 2021).

Once ST concepts are selected then one or more questions that address each concept are created or collected (from a list of questions) to use in the initial field testing of the ST concept inventory (at a particular level). Identification of particular research methods used to validate and determine reliability for each question in the concept inventory is beyond the scope of this paper.

A sample ST concept inventory question for secondary school (for the Level 2 ST concept of explaining bathtub dynamics) could be:

The Junior Class has fundraisers all year long. If the amount of money going into the Junior Class account (inflow) and the amount of money spent on needed equipment, etc. (outflow) follows the graphs shown at the right, how is the level of money in the Junior Class account changing over time?



a. The money in the account is increasing at an increasing rate.
b. The money in the account is increasing at a decreasing rate.
c. The money in the account is decreasing at an increasing rate.
d. The money in the account is decreasing at a decreasing rate.
e. The money in the account is staying the same.
f. It is not possible to tell from the information given.

Call to Action

We call on all of those educators and practitioners who have endeavored to assess systems thinking skills of their students/stakeholders to join us in our efforts to collect ST assessment questions. For each question submitted the name and email of the person submitting the question will be required. The questions can be in any format used to assess ST. If the questions are not in multiple choice format we can reformat the question by contacting its author during the reformatting process. We have created an online process for submitting an ST assessment question. See Appendix II for a list of the questions you will be asked to complete on the Google form if you decide to submit an ST assessment question.

Conclusion

It is important that the SDS take a leadership role in providing guidance for the assessment of ST concepts in pre-college education. The society has a long and practiced history of applying systems thinking analysis to important systemic problems of global importance. The value of designing a hierarchical list of systems thinking skills that includes the development of system dynamics models to test policies will result in a list that will be more complete and practical than could be developed by educators less versed in the need for operationalizing mental models. We, pre-college educators who have used ST/SD in our instruction for decades, know that the concepts in our current ST list are within the reach of pre-college students. If we develop useful ST concept inventories at the primary school, middle school, and secondary school levels we have an opportunity to impact the activities that will be considered central to the inclusion of ST concepts for pre-college instruction moving forward.

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Appendix 1:

Guiding Principles for Creating Multiple Choice Questions (Eberly Center, 2021).

Strategies for creating objective test questions:

- Write objective test questions so that there is one and only one best answer.
- Word questions clearly and simply, avoiding double negatives, idiomatic language, and absolutes such as “never” or “always.”
- Test only a single idea in each item.
- Make sure wrong answers (distractors) are plausible.
- Incorporate common student errors as distractors.

- Make sure the position of the correct answer (e.g., A, B, C, D) varies randomly from item to item.
- Include from three to five options for each item.
- Make sure the length of response items is roughly the same for each question.
- Keep the length of response items short.
- Make sure there are no grammatical clues to the correct answer (e.g., the use of "a" or "an" can tip the test-taker off to an answer beginning with a vowel or consonant).
- Format the exam so that response options are indented and in column form.
- In multiple choice questions, use positive phrasing in the stem, avoiding words like "not" and "except." If this is unavoidable, highlight the negative words (e.g., "Which of the following is NOT an example of…?").
- Avoid overlapping alternatives.
- Avoid using "All of the above" and "None of the above" in responses. (In the case of "All of the above," students only need to know that two of the options are correct to answer the question. Conversely, students only need to eliminate one response to eliminate "All of the above" as an answer. Similarly, when "None of the above" is used as the correct answer choice, it tests students' ability to detect incorrect answers, but not whether they know the correct answer.)

Appendix 2:
The format and location of the Google form created to allow interested persons to submit an ST assessment question that addresses one of the ST concepts in the list in part I of this paper:

Section 1:
Name: (yours)
Email: (yours)
Do you give permission to freely distribute your assessment question through CLE and/or SDS?
Your assessment question: (Note: if multiple choice, please provide correct and distractor choices)
(File or image upload available for question)
The answer for your assessment question:
(File or image upload available for answer)
What is the Systems Thinking category (from the list in part I of this paper) into which this question fits? (note: "other" category is provided)

Section 2:
For which discipline would this question be appropriate? ("other" discipline is provided)
What is the student age group for this question?
What is the purpose of the question?
What is the level of ST difficulty for the age group using this question?
What pre-requisite knowledge is required to answer the question?

The location of the submission form is: *https://forms.gle/6hhP2csJky8fexTRA*

Answers to the questions in Section 1 are required. The answers to the questions in section 2 are helpful but not required. We will make sure that all those who submit a question will receive a copy of the questions collected, updated at regular intervals. Eventually this set of questions will be available through the Creative Learning Exchange (clexchange.org).