Chapter 2

Organization and Representation of Engineering Systems

Objectives

- To define the attributes of an engineering design problem and to describe the relationship among the purpose, environment, and form of an artifact;

- To describe a simple cognitive model for how the human mind stores, organizes, and retrieves information;

Objectives

- To draw concept maps consisting of circle-and-arrow diagrams that illustrate ideas and the relationships between them; to construct concept maps for a variety of simple situations;
- To define a hierarchy and to discuss why hierarchies are important in representing ideas; also, to successfully use hierarchical concept maps to illustrate the organization of parts in a system.

What We Think About How We Think

- You are the owners and operators of your own brain, but it came without an instruction book. We need to learn how we learn.

- Just as a driver can achieve better mileage and performance from an automobile by knowing minimally about how an engine and transmission work, a skilled problem solver can, similarly, achieve better mileage and performance from his or her cognitive machinery by understanding how that works!

Doing Simple Math

EASY

$$2 \times 7 = ?$$

$$5 \times 4 = ?$$

$$2 + 0 = ?$$

$$9 + 6 = ?$$

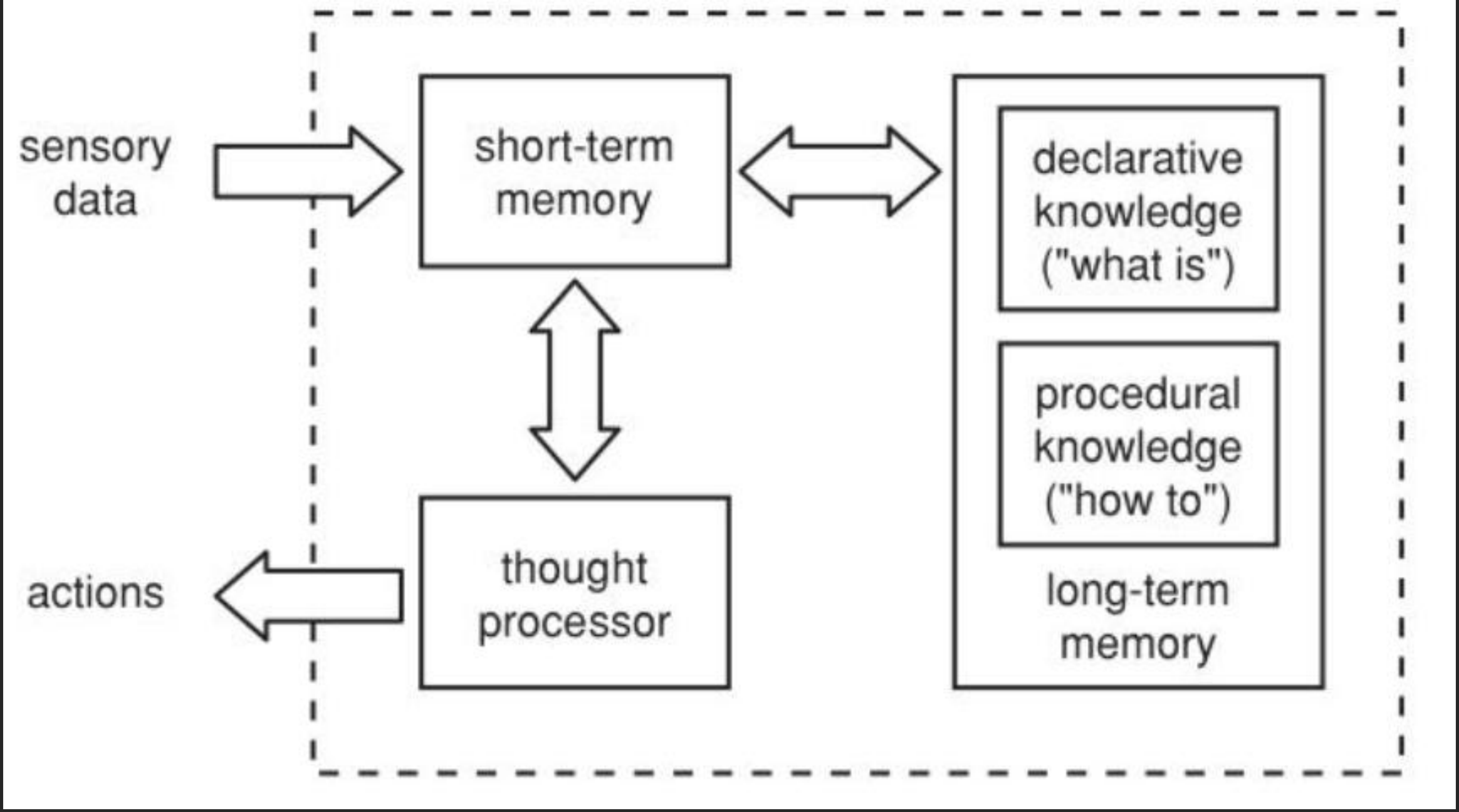
We're so proficient at solving these kinds of problems that we couldn't even explain how we do it; we simply know the answer.

NOT SO EASY

$$4132 \times 57 = ?$$

The obstacle to solving this problem is our memory: specifically, our inability to keep track of all the partial results and access them when we need them.

Human Information Processing System



A Model for Cognitive Processing

- Long-term memory, the extremely large store for facts we accumulate over a lifetime. This includes declarative or “what is” knowledge, as well as procedural or “how to” knowledge;

- Short-term memory, a much smaller store for bits of information we’re currently working with;

- A thought processor, which operates on facts in short-term memory.

"How To" Knowledge and Problem Solving

- Up to this point, we've focused on the representation of knowledge used in answering a question of the form "what is."

- This type of knowledge is often called declarative knowledge, because it declares facts about concepts.

- A second type of knowledge called procedural knowledge addresses questions about "how to" do something, and is the basis for all types of human problem solving.

A Model for Cognitive Processing

- According to this model, short-term memory temporarily stores information gathered through our senses (hearing, seeing, etc.) before passing it on to long- term memory.
- Research has shown that if information from our short-term memory doesn’t successfully transfer to long-term memory within a few seconds, then we forget the information.
- Further, all thought processing occurs in information in our short-term memory stores, and concepts our long-term memory stores must transfer back to short-term memory before we can work with them.
- Short-term memory, then, is the bottleneck in this system

Using Rules to Represent Chunks of Procedural Knowledge

- A common approach to modeling procedural knowledge is to represent small chunks of procedural information as condition-action pairs as rules of the form:
- IF some condition exists,
- THEN perform some action.

Using Rules to Represent Chunks of Procedural Knowledge

- When the “thought processor” activates a given rule, it checks the condition against the set of facts in memory. If the condition is true—if it matches a fact or set of facts—then we say that the rule fires and the action is performed.

IF	X is an animal
	and X can fly
	and X has feathers
THEN	X is a bird

Using Rules to Represent Chunks of Procedural Knowledge

- More than one rule can apply.
- In this case there is more than one correct answer.

IF	the goal is to stay dry and it is raining
THEN	carry an umbrella
IF	the goal is to stay dry and it's raining
THEN	wear a raincoat

Using Rules to Represent Chunks of Procedural Knowledge

- However, we could re-learn the first rule as:

IF	the goal is to stay dry
	and it's raining
	and you have a free hand
THEN	carry an umbrella

In this case, if you don't have a free hand, only the second rule, whose action is to wear a raincoat, would fire. Many problems have more than one possible solution and our brains are able to keep track of these options.

Linking Chains of Rules to Solve Complex Problems

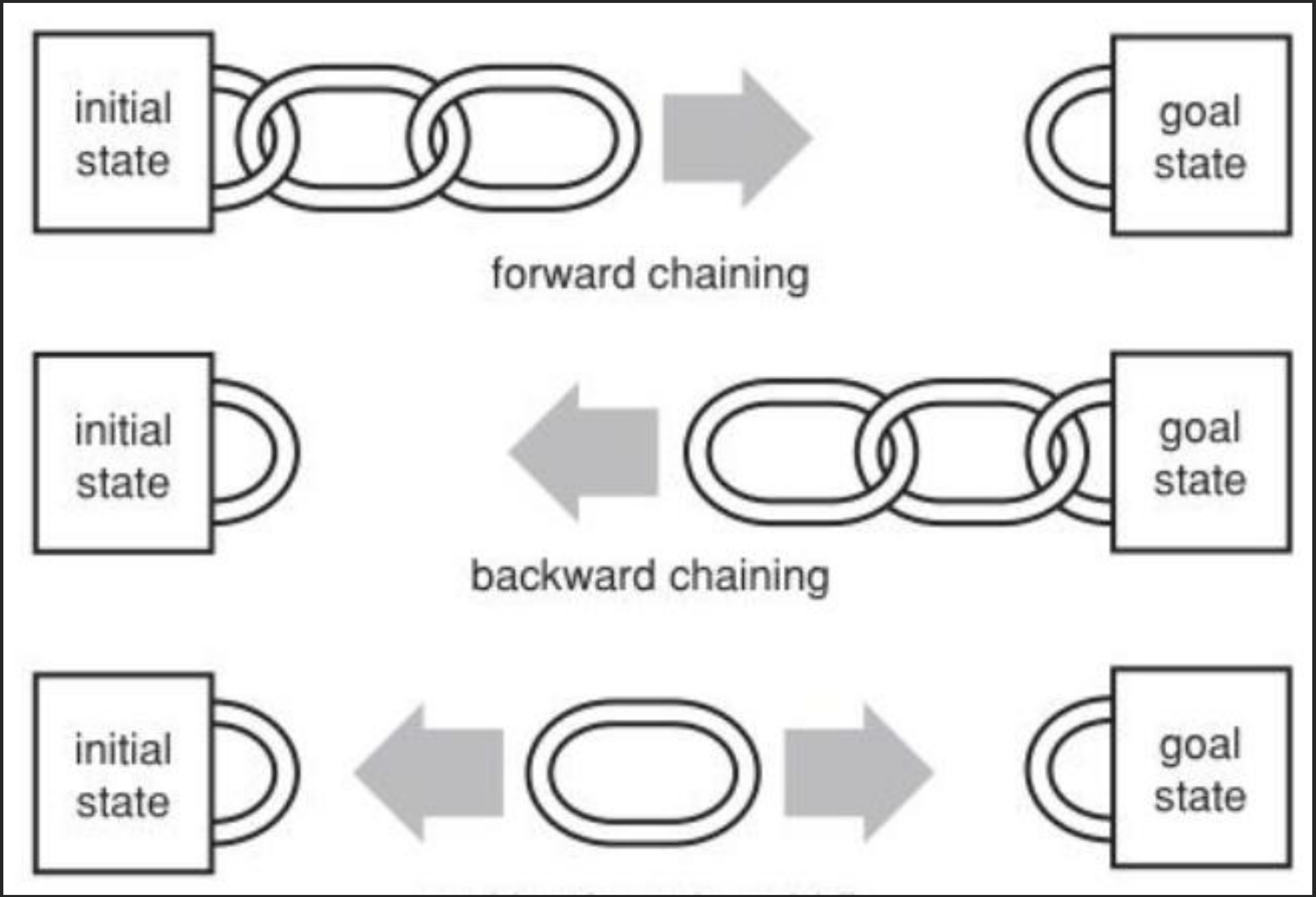
- Sometimes, we're fortunate enough to get a perfect match on a single rule that completely solves a problem for us.

- Most of the time, however, we find that no direct solution exists, so instead we have to creatively piece together a solution as a series of steps between our starting point and our goal.

Linking Chains of Rules to Solve Complex Problems

- Three different strategies for linking up a complete solution are:
  - Working forward from the starting point toward the goal, called forward chaining,
  - Working backward from the goal, or backward chaining, or
  - Working from the middle

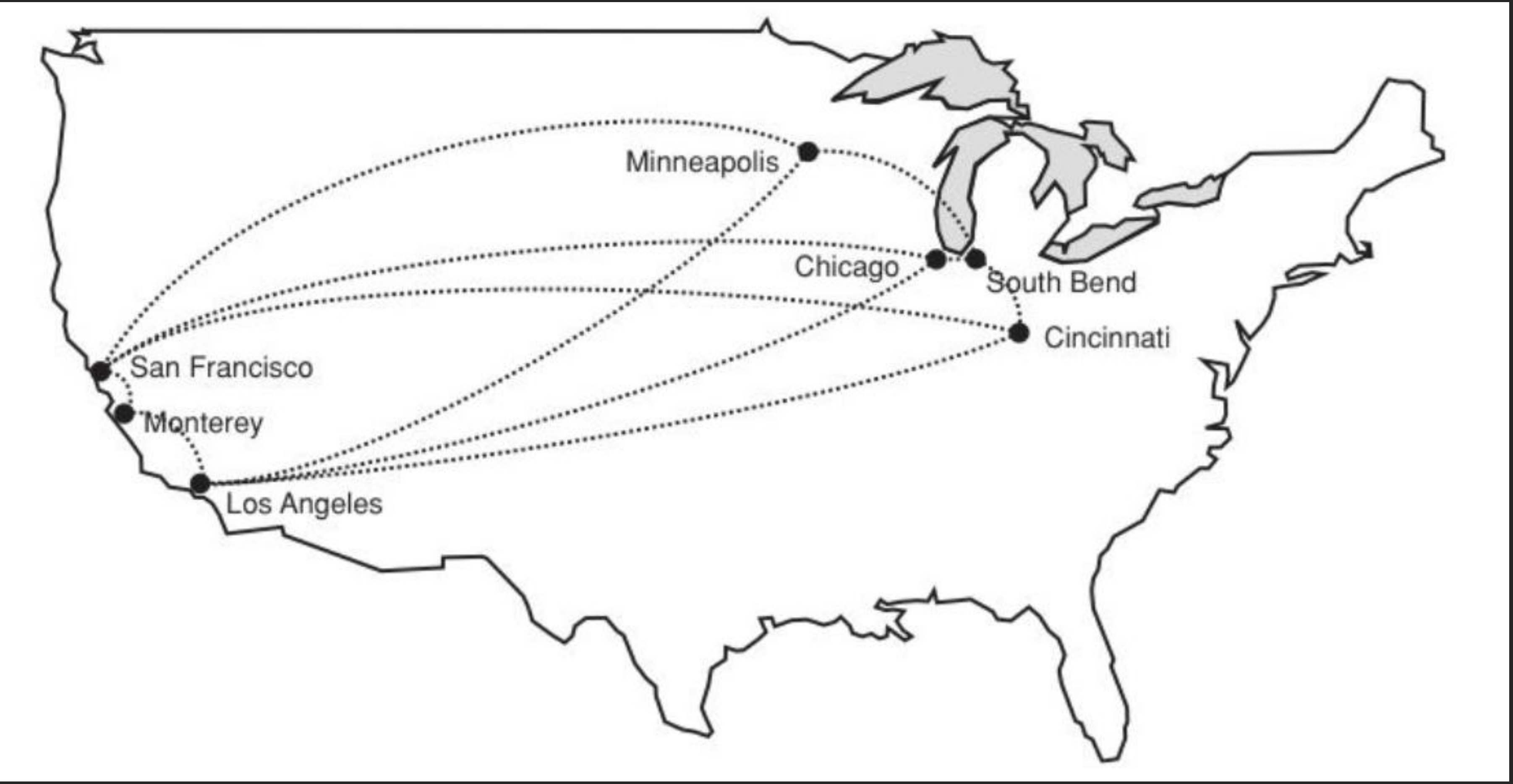
Linking Chains of Rules to Solve Complex Problems



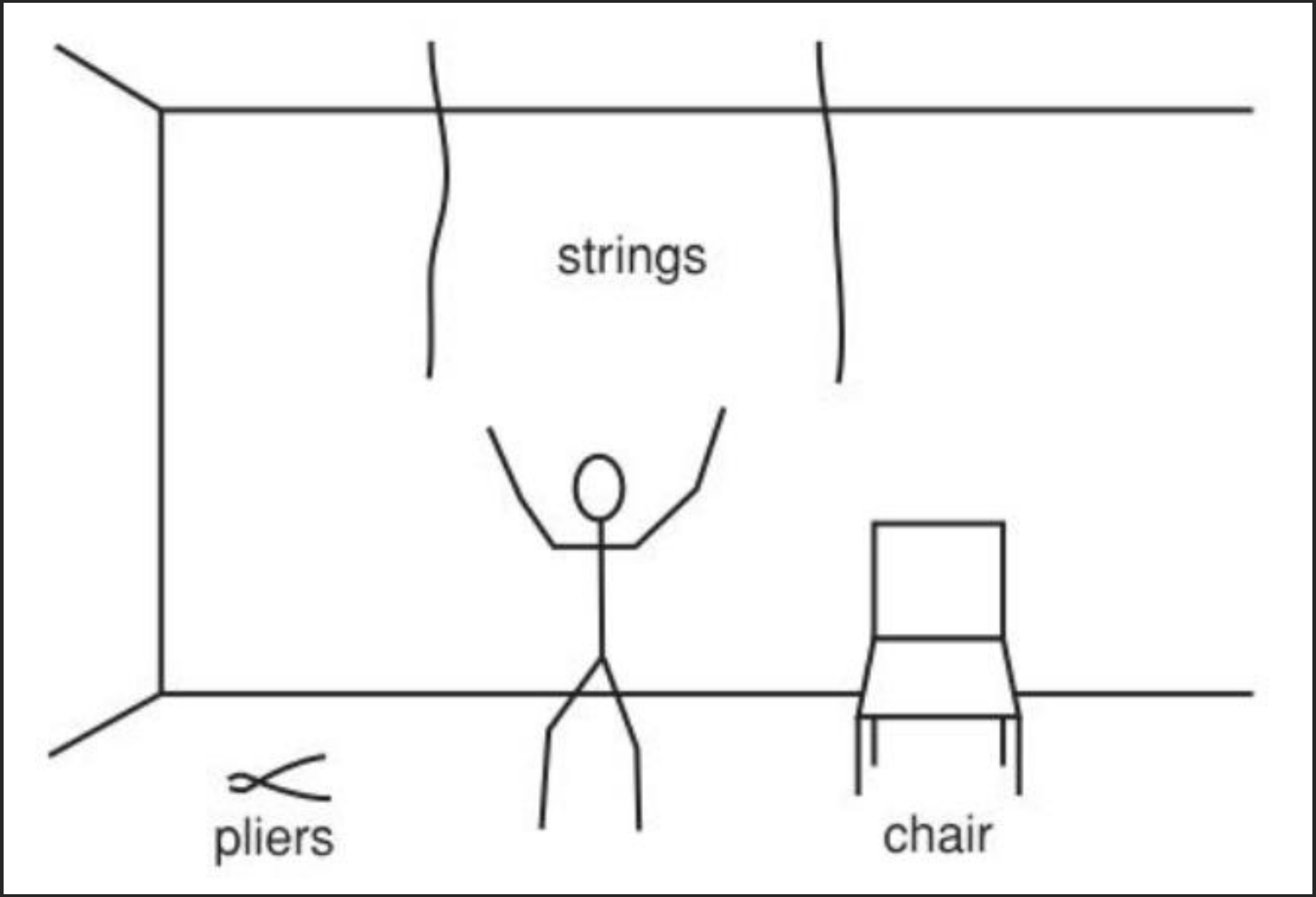
Linking Chains of Rules to Solve Complex Problems

One example of chaining together a solution is booking flights between two cities when no direct flight between them exists. Suppose, for example, that we want to book a flight between South Bend, Indiana and Monterey, California. Since there are no direct flights between South Bend and Monterey, it's necessary to find a route composed of flight segments through other airports.

Linking Chains of Rules to Solve Complex Problems



Another Problem



Mind and Brain

- The National Research Council study How People Learn discusses three key findings at the convergence between research in cognitive psychology and neuroscience:

1. Learning changes the physical structure of the brain.

2. These structural changes alter the functional organization of the brain; in other words, learning organizes and reorganizes the brain.

3. Different parts of the brain may be ready to learn at different times.

Concept Maps

- A concept map is a network diagram or graph, where the nodes correspond to concepts and the edges correspond to relationships between concepts.
- Labels on the nodes and edges indicate the names of the concepts and relationships.

Concept Maps

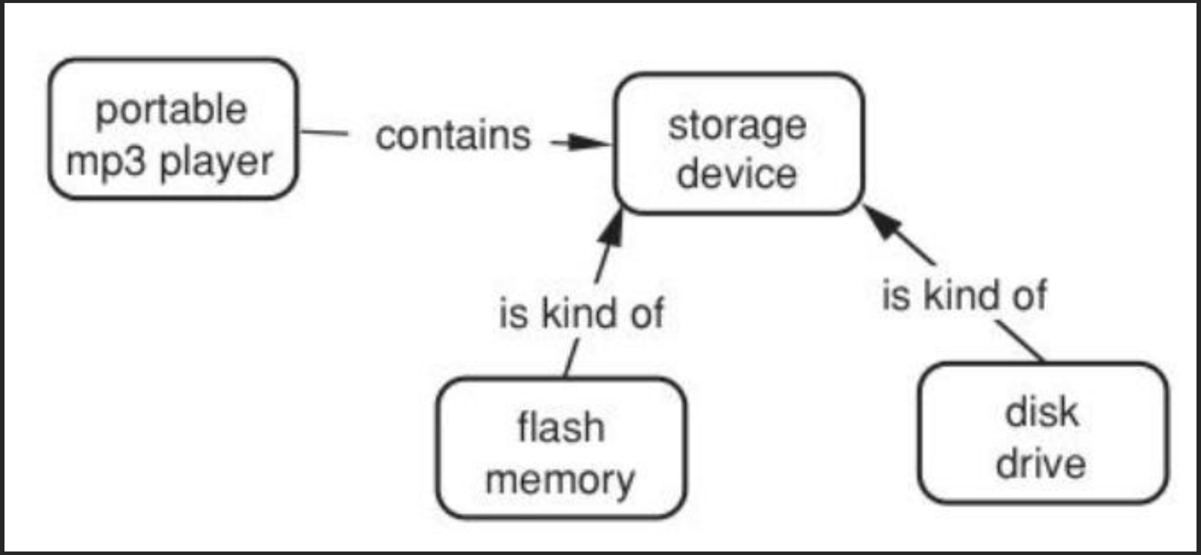
- Propositions are statements formed by connecting two or more concepts with relationships.

- We “pronounce” propositions in a concept map by first stating the name of the object at the tail of the arrow, then the name of the relationship, and finally the name of the relationship at the head of the arrow.

Concept Maps

The Figure illustrates a concept map focused on the concepts of storage devices for a portable MP3 player, that contains the following propositions:

- a portable MP3 player contains a storage device
- flash memory is a kind of storage device
- a disk drive is a kind of storage device



How to Build a Good Concept Map

1. Drawing a concept map helps you brainstorm and organize ideas, thus facilitating a deeper knowledge of material;

1. Monitoring your ability to draw a concept map for a body of knowledge tests how well you understand it; and

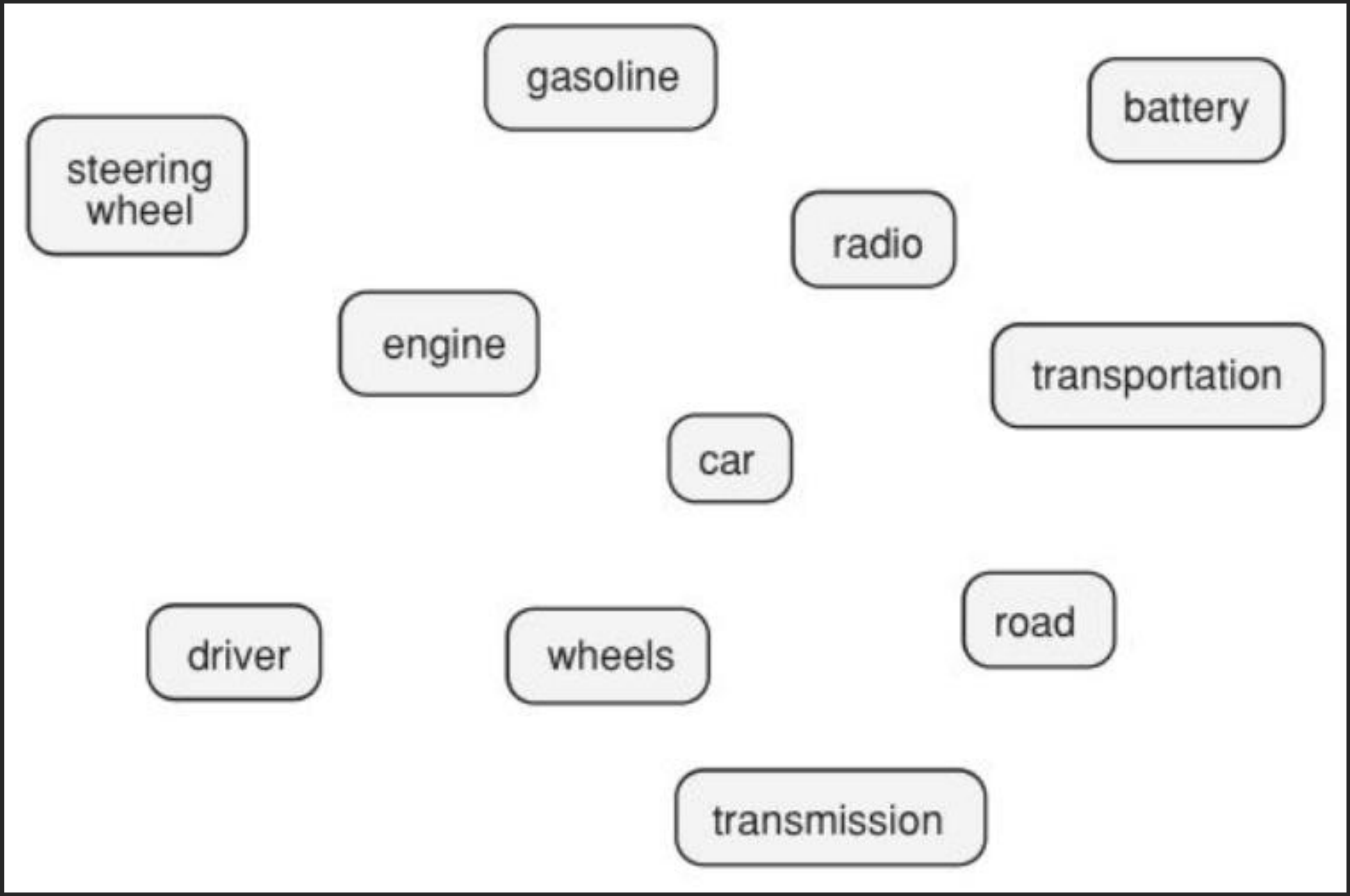
1. A well-constructed concept map is an effective tool for presenting ideas to others.

A Few Things

- Concept maps aren’t right or wrong.
- They are never really complete.
- The first step is to identify the domain by posing a question
  - e.g. what is a car?

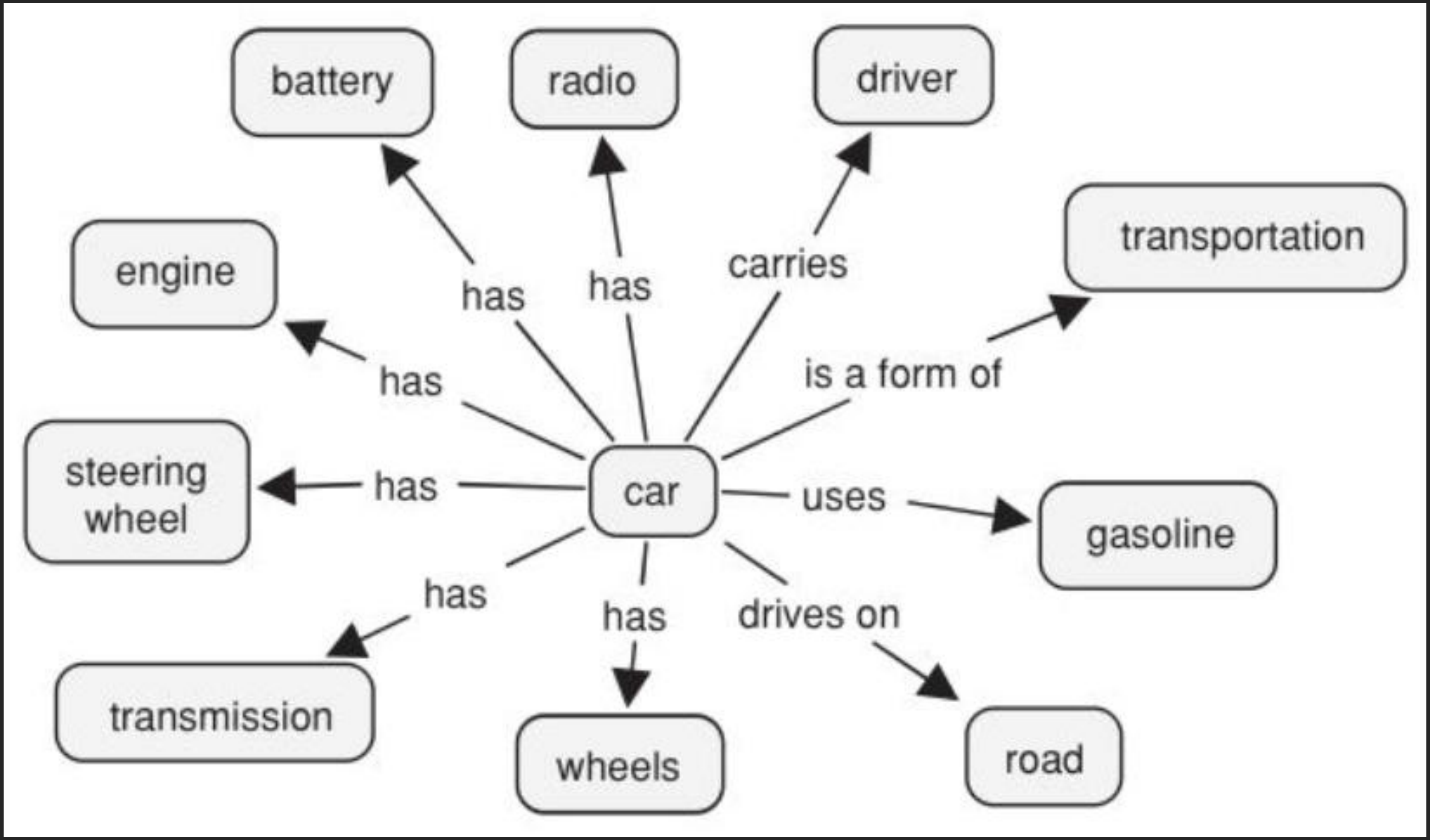
Car Concept Map

Start by listing Concepts



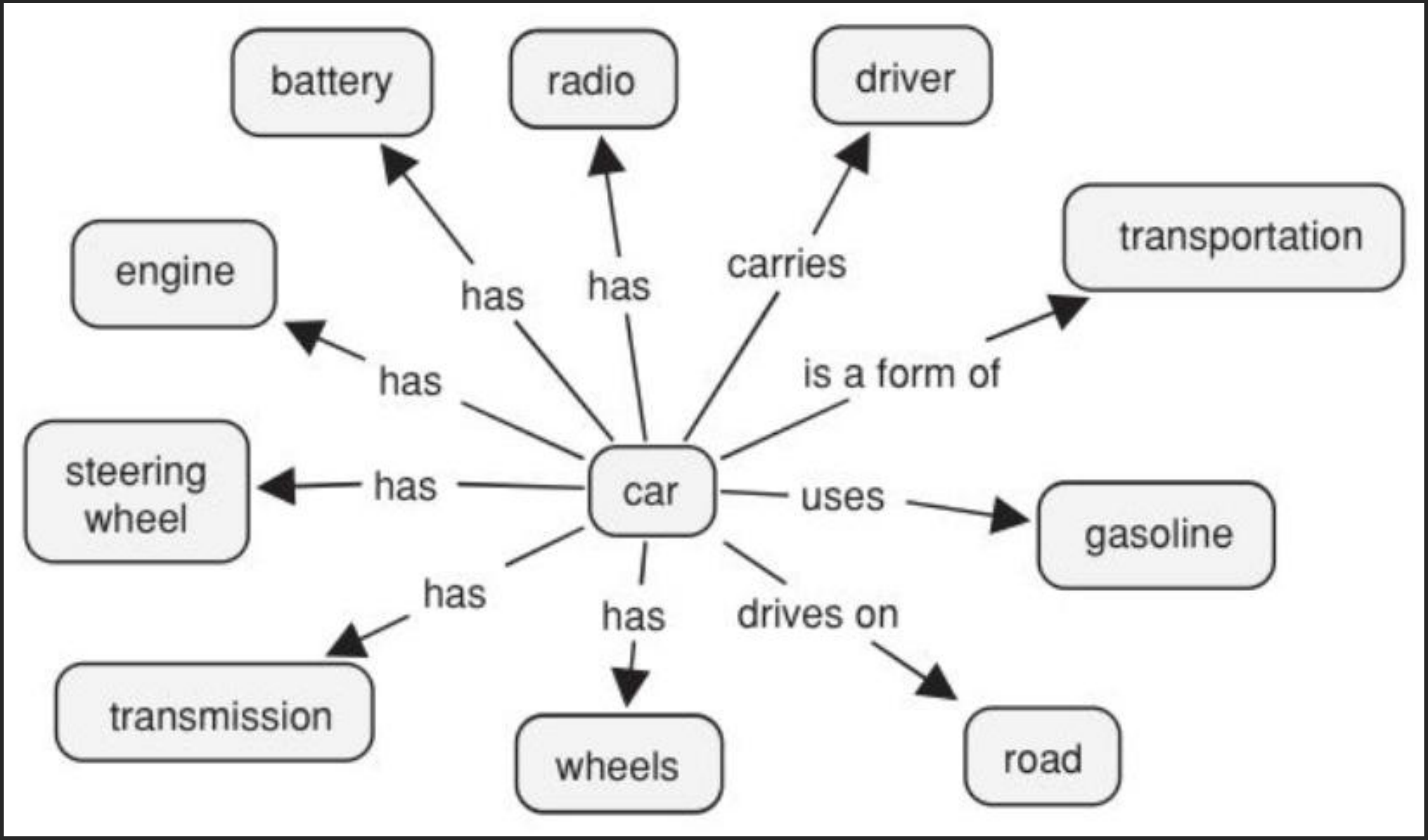
Car Concept Map

Link them with relationships.



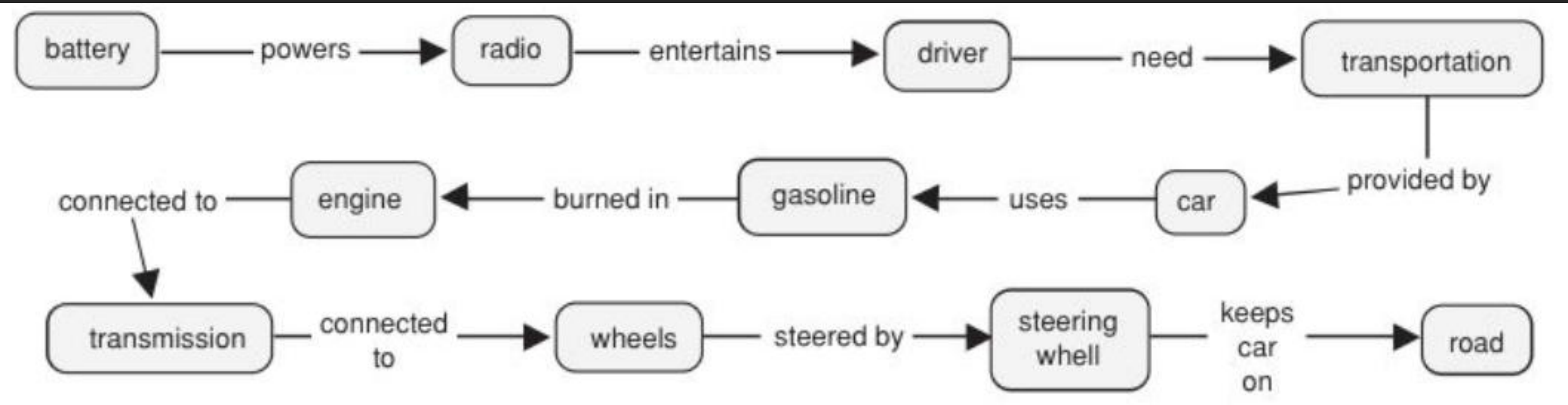
Car Concept Map

Link them with relationships.



Car Concept Map

Not a Good organization for our concept map



Car Concept Map

- Creating a good (specifically memorable) concept map:
- Break map down into manageable chunks (5-9 items with both concepts and relationships

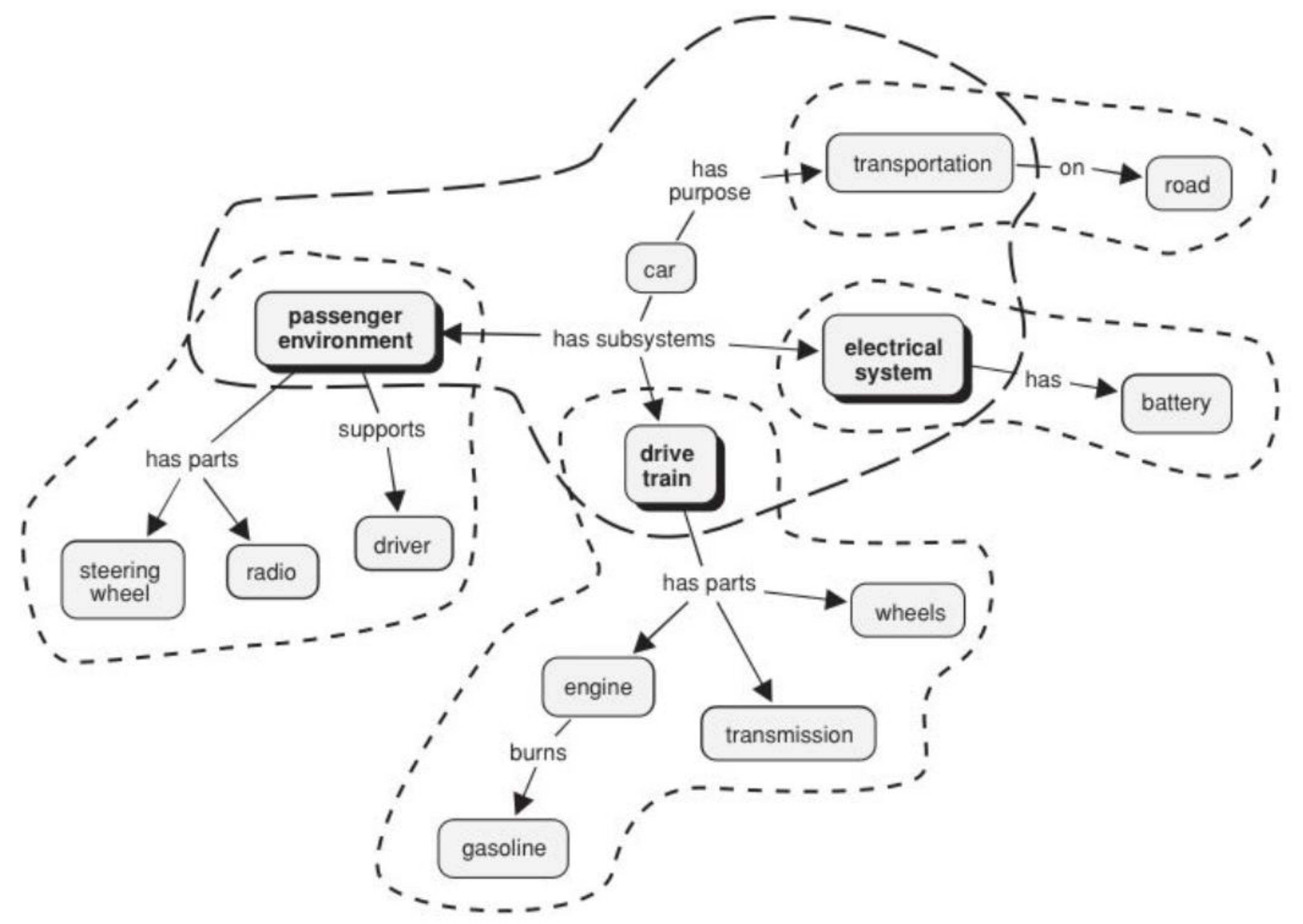
- Bind concepts into smaller groups (usually need to add concepts)

- New concepts added:
    - Passenger environment, drive train, and electrical systems

Car Concept Map

- We have also introduced a pleural relationship, drawn as an arrow that splits into multiple arrows.
- This plural relationship groups relationships of the same type together and effectively increases the capacity of a chunk.
- Dotted lines enclose each of five suggested chunks in the graph.
- The central chunk consists of the concept of "car," its three subsystems, and its purpose—"transportation." Peripheral chunks linked to the central chunk further describe a car's subsystems and its purpose.

Car Concept Map



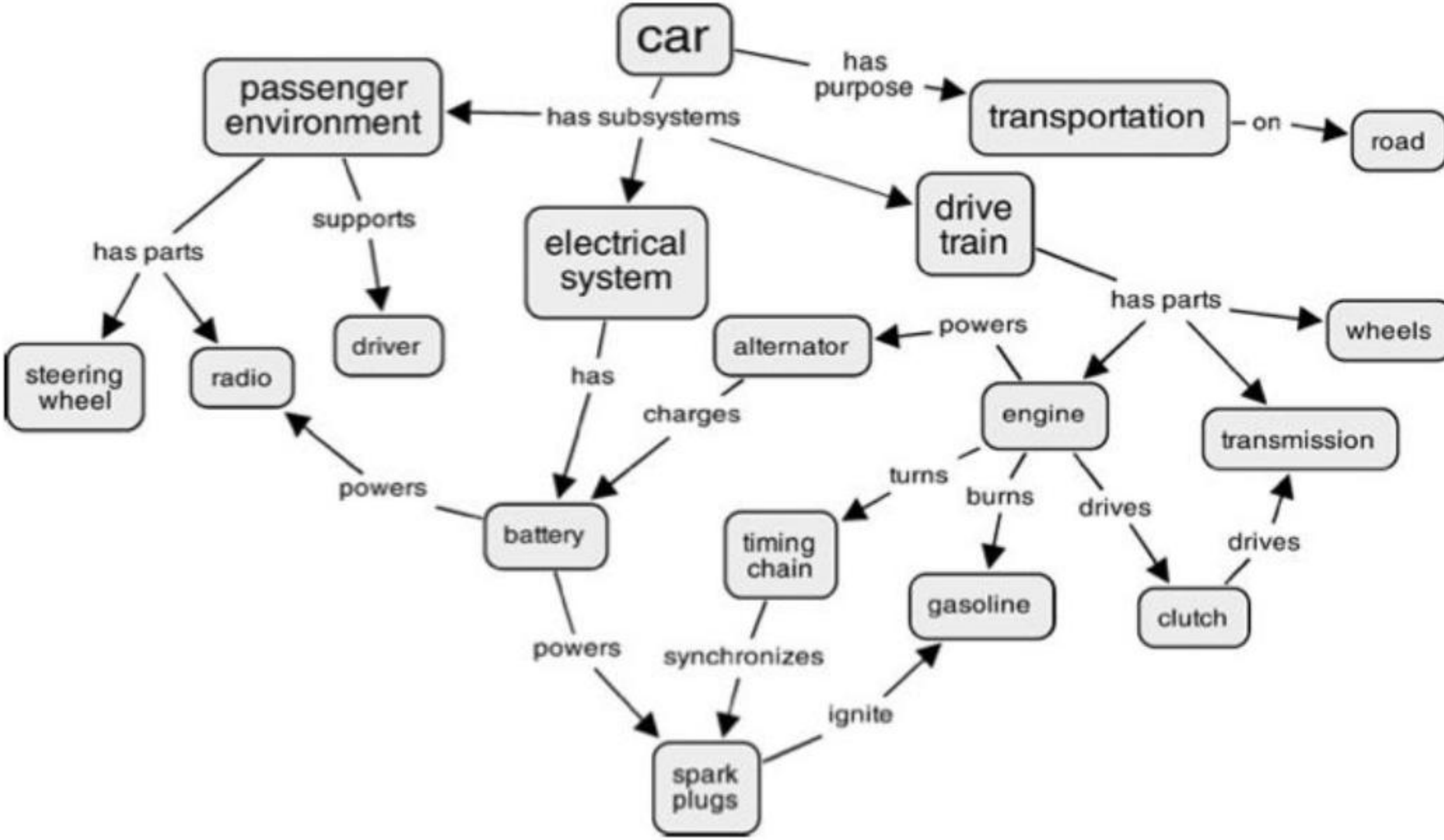
Car Concept Map

- The final step in drawing a concept map is to look for additional cross-links be- tween concepts, both within chunks and between chunks in different parts of the map.
- This step provides significant insight toward understanding a domain.
- For ex- ample, the radio—a part of the passenger environment—is also tied to the electrical system and powered by the battery.
- Similarly, we may ask if there are connections between the electrical system and the drive train.

Car Concept Map

- After some reflection, you may have the insight that some cars have electric motors, but there are also connections between the drive train and the electrical system in cars with gasoline engines.
- The question is, how do you discover these additional connections?
- One approach I strongly recommend is using a combination of brainstorming and research.

Final Car Concept Map

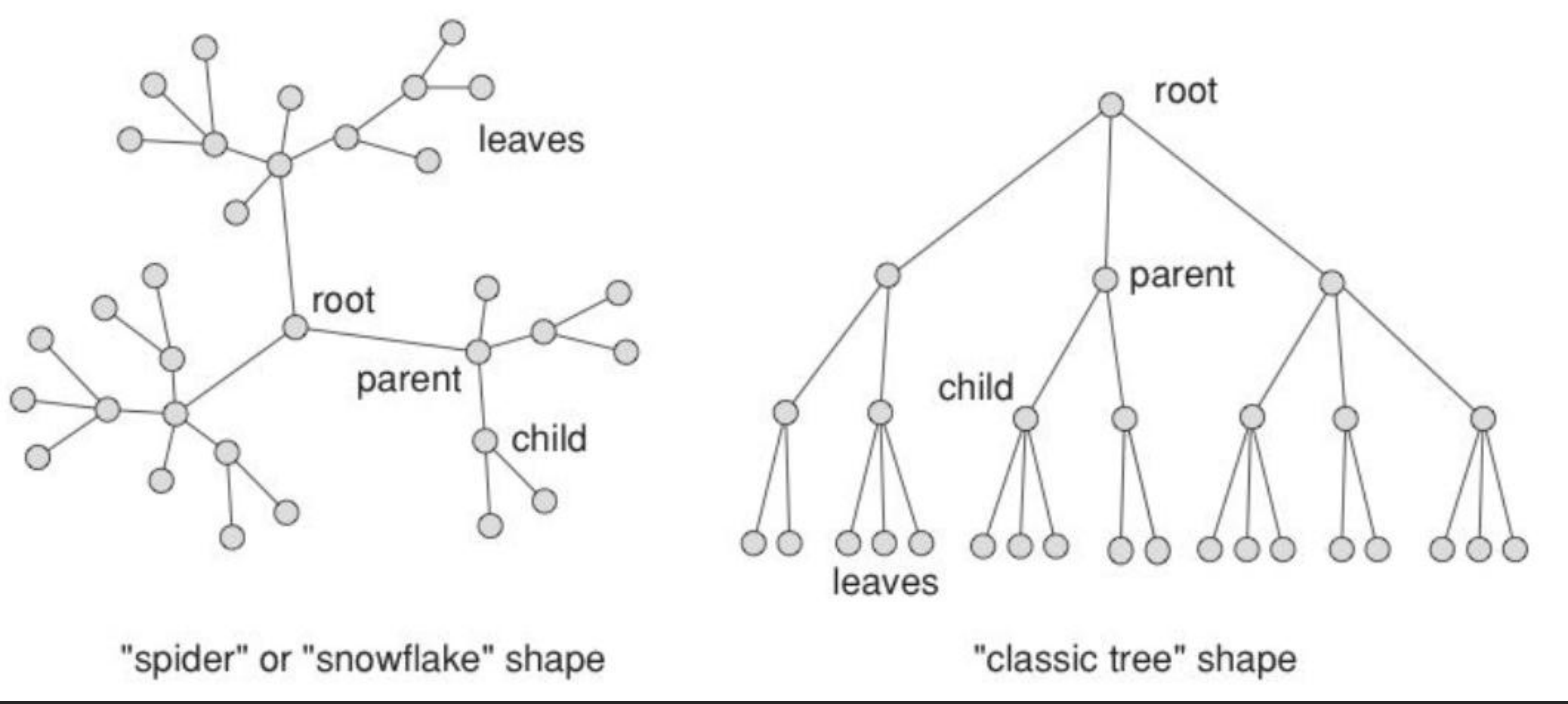


Hierarchies

- Some organizations of concepts maps are easier to understand, are more meaningful, and are easier to recall than other.
- We determined that a central concept linked to a few supporting concepts is a particularly effective organization.
- These concepts themselves were then linked to a few supporting concepts, and so on.
- Such organizations are termed hierarchies.

Hierarchies

- A map of a hierarchical organization is a graph with a characteristic shape, called a tree.

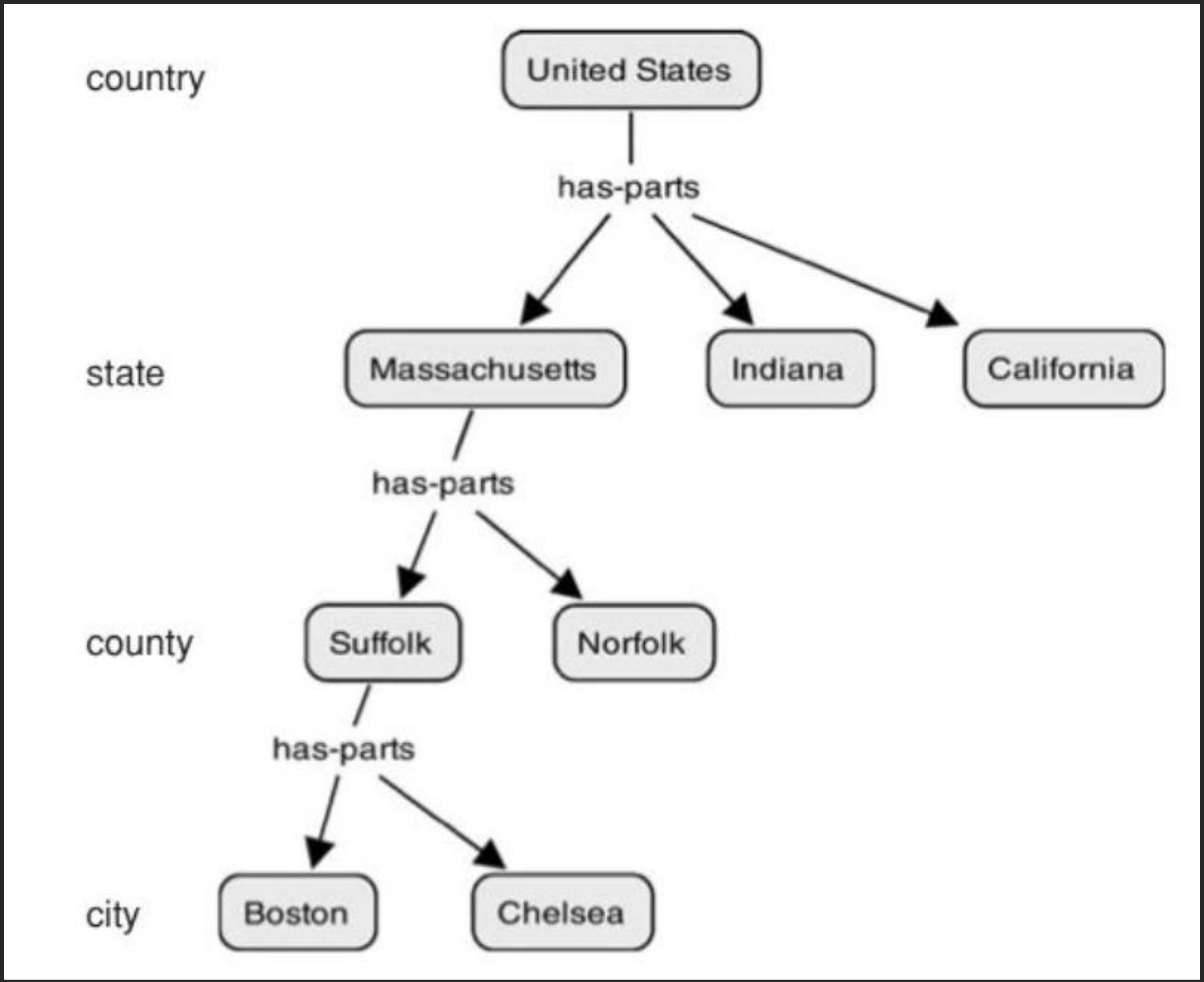


Parts Hierarchies

- A parts hierarchy is a hierarchical concept map that illustrates how a complex object is composed of a set of parts, which may themselves be com- posed of a set of smaller parts.
- A relationship labeled “contains,” “has,” or “has-part” directed from parent to child expresses the notion that a child concept is a part of a parent.
- Equivalently, we could use a “is-part-of” relationship directed from the child to the parent.
- Note that concepts in a parts hierarchy may represent either physical objects or abstract ideas. Just as a physical object such as a bicycle has handlebars and wheels, a story has a plot and a setting, and a typical engineering homework problem has an unknown quantity and assumptions.

Parts Hierarchies

- In a strict hierarchy, as represented by a tree, each node has exactly one parent, except for the root, which has none.

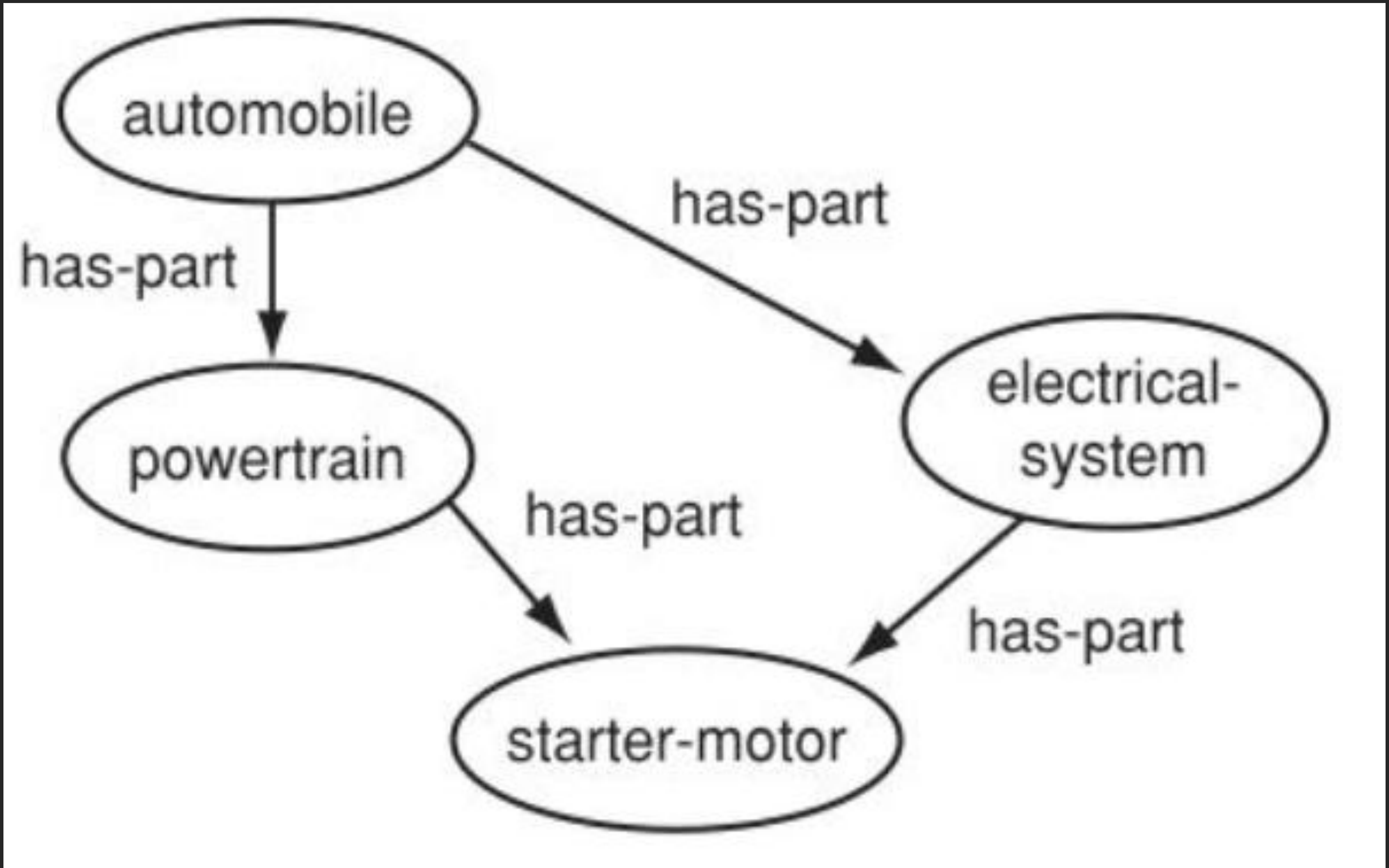


Parts Hierarchies

- Oftentimes, however, it's convenient to think of one concept as part of two different things. In a car, for example, a starter motor may be thought of as part of both the power train and the electrical system.

- We will still refer to such a map as a parts hierarchy, but the graph no longer qualifies as a tree because the "starter-motor" node has two arrows pointing toward it and hence two parents.

Parts Hierarchies

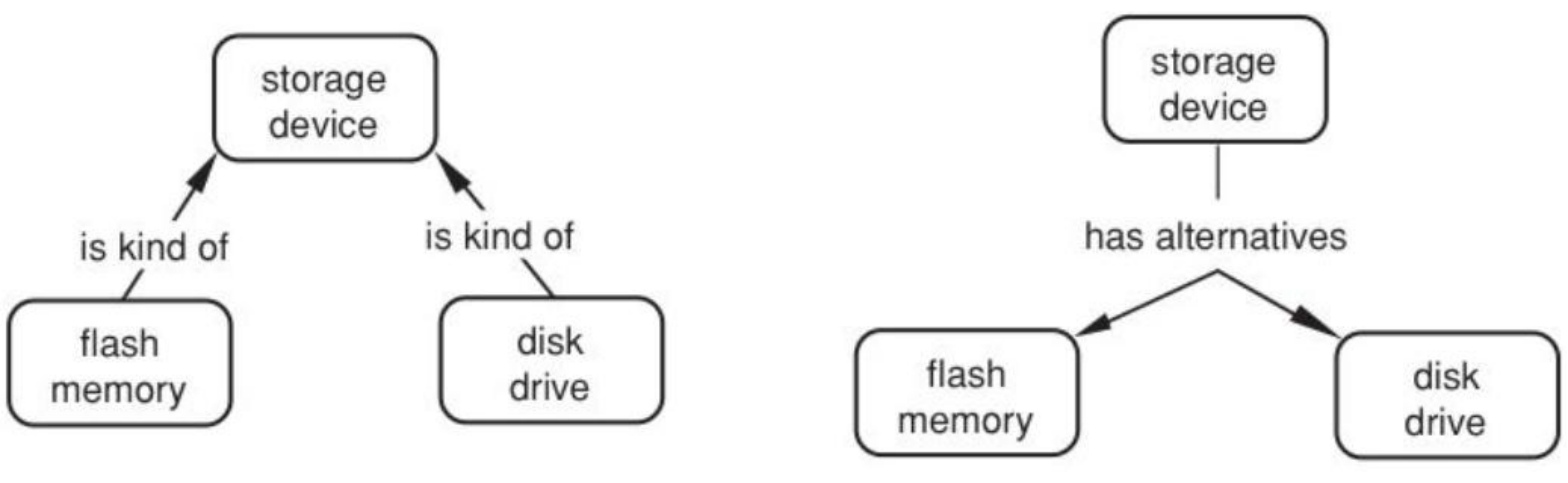


Not a tree as starter motor has two parents but is still a hierarchy

Class Hierarchies

- We can organize concepts into classes.
- A class may be defined as a set of concepts that share a common set of attributes or properties.
- A class hierarchy is also called a taxonomy.
- Here more general classes of things are successively broken down into more specific classes of things.

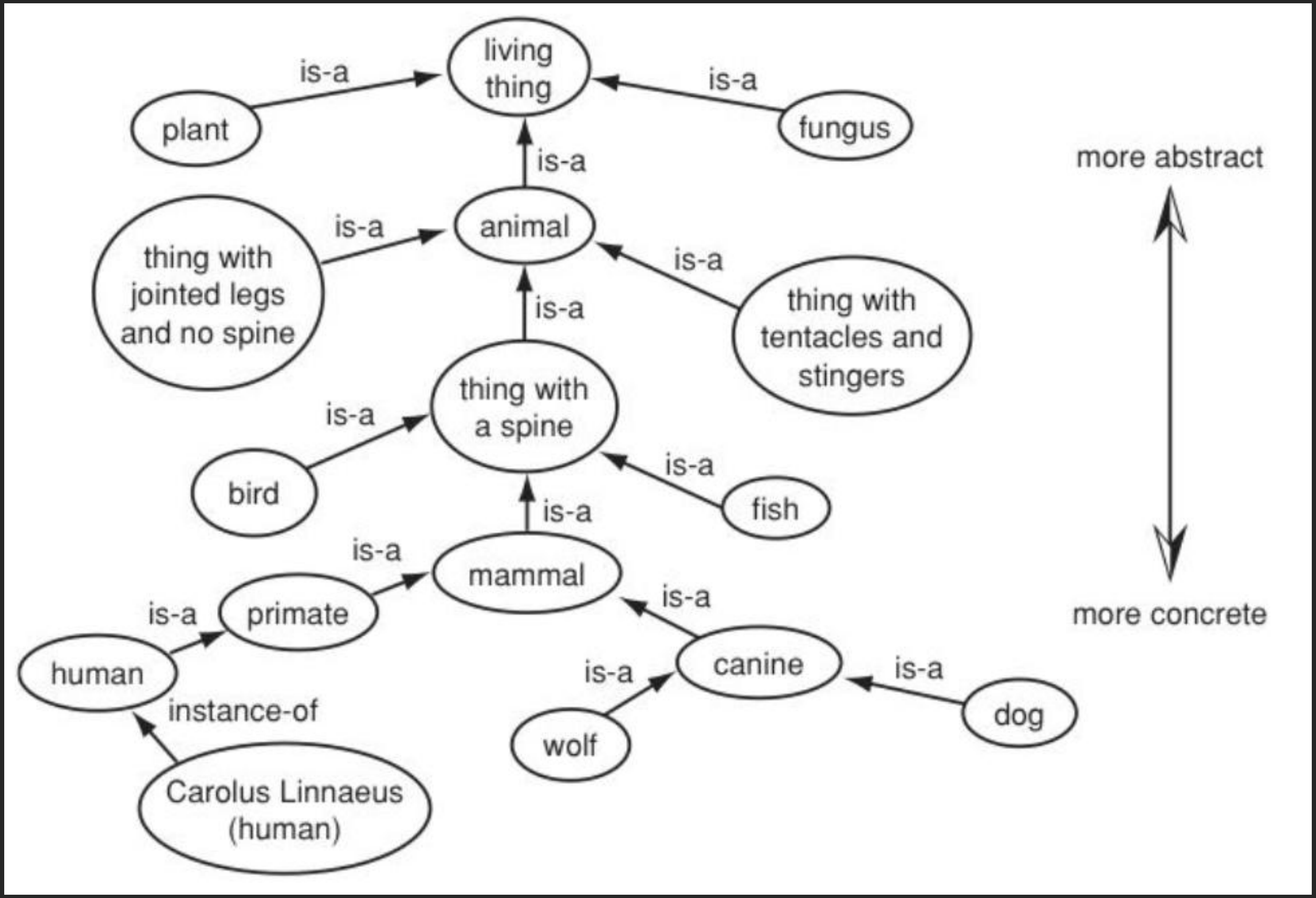
Class Hierarchies



Two ways of expressing flash memory and disk drives belong to the class of storage devices (inheritance relationships).

Class Hierarchies

- A particularly famous class hierarchy is the taxonomy of all living things developed by the Swedish biologist Carolus Linnaeus in the mid-1700s.



This taxonomic structure is based on the form of things. However, when considering man-made things we often organize things by purpose.

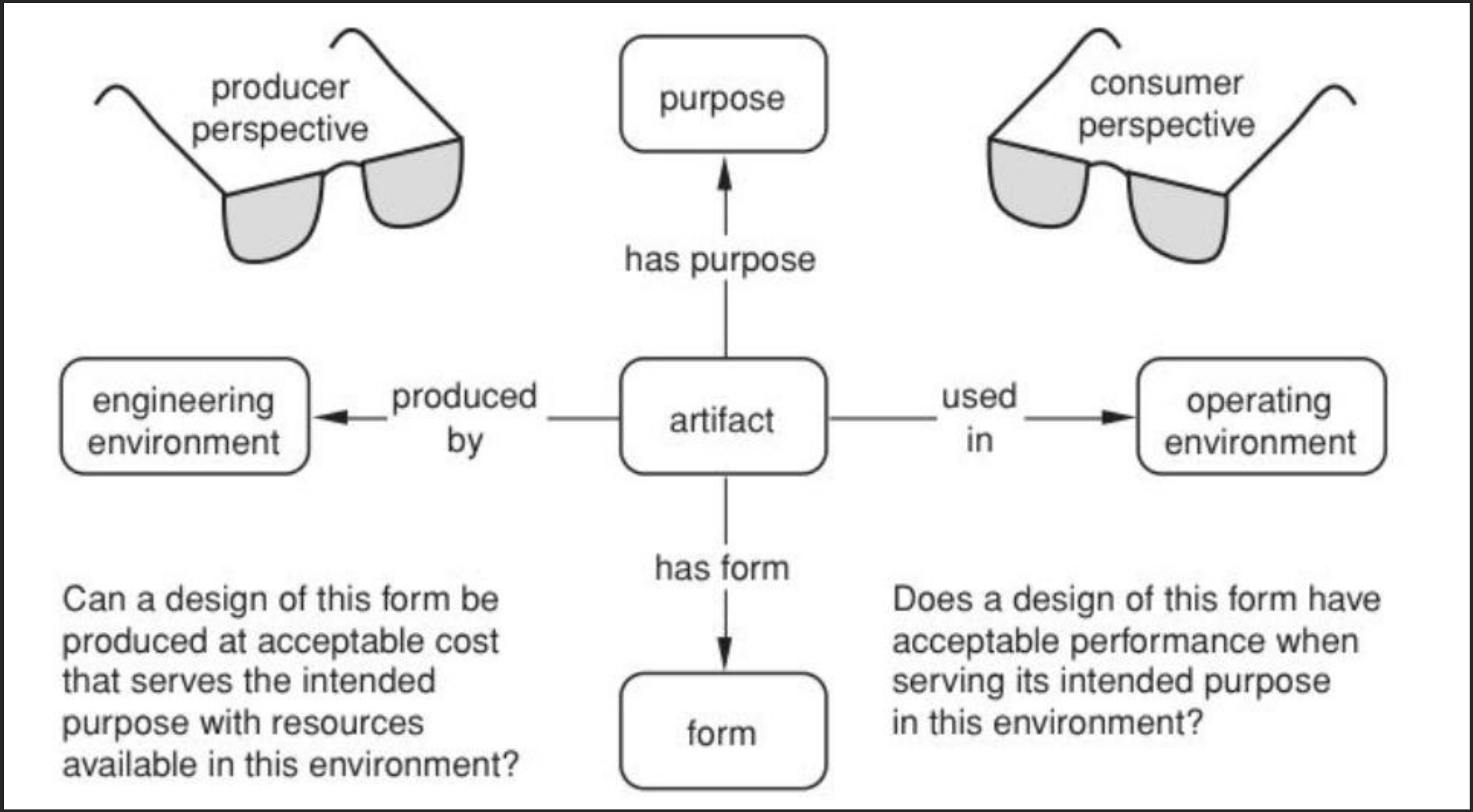
Purpose, Environment, and Form

- All artifacts have both a form and a purpose, and to accept an artifact, its form must be appropriate to its purpose.

- Engineers approach the problem from two ways:

  – From the operating environment that will use the artifact, and
  – The engineering environment that will produce it.

Purpose, Environment, and Form



Purpose, Environment, and Form

- The operating environment includes all characteristics of the surroundings in which it will be used:
  - Effects of physical environment (temperature, humidity, gravity etc.),
  - Socioeconomic conditions (funding, environmental regulations, operating and manufacturing standards, customs etc.),
  - The particular ways in which people interact with the artifact (how they operate and maintain or repair the artifact);
  - The ways other artifacts may interact with it (automobile engine and its transmission).

Purpose, Environment, and Form

- Similarly the engineering environment includes:
  - The people involved in the design and manufacturing of the artifact;
  - The tools and methodologies used in the design;
  - Available materials and technology; and
  - Factories and production facilities.

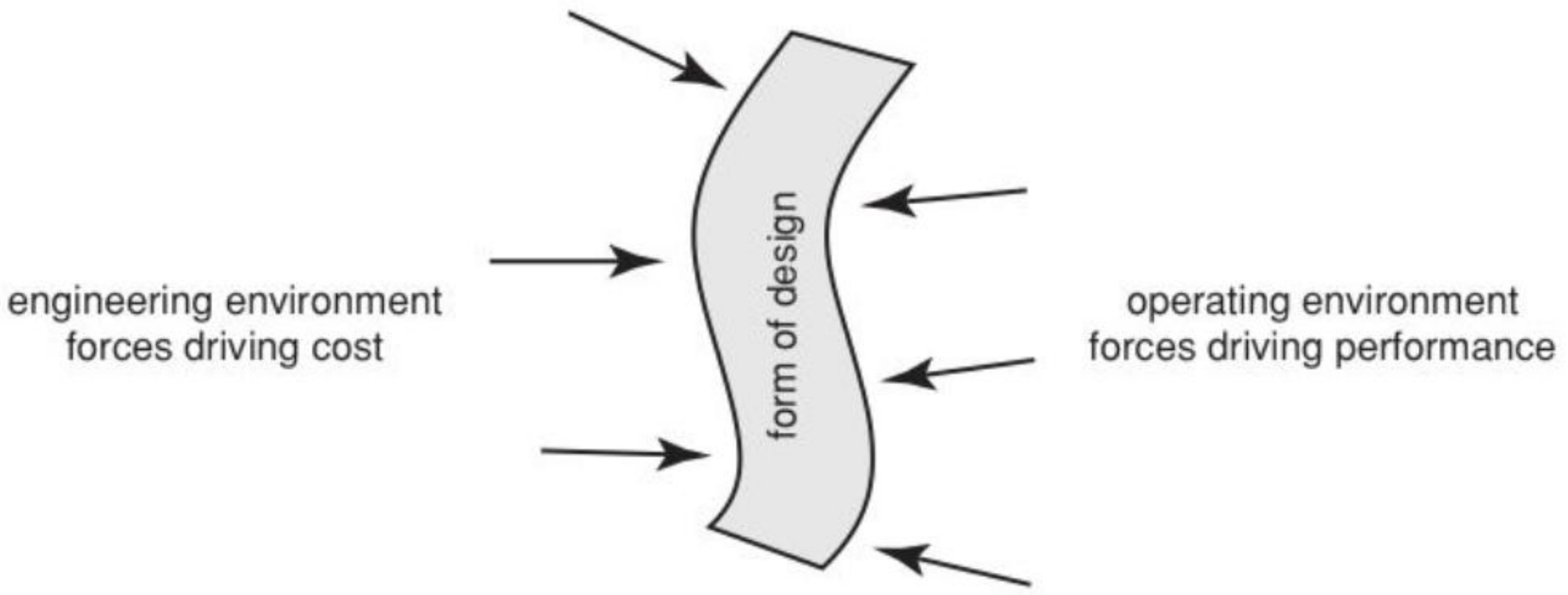
Requirements, Specifications, and the Forces That Shape a Design

- During the design process, engineers will continually refine the form of an artifact until it's acceptable within the operating and engineering environments.

- One way of visualizing this process is to imagine "forces" in the environment that impel the engineer to change the shape of a design until it reaches an acceptable form.

Requirements, Specifications, and the Forces That Shape a Design

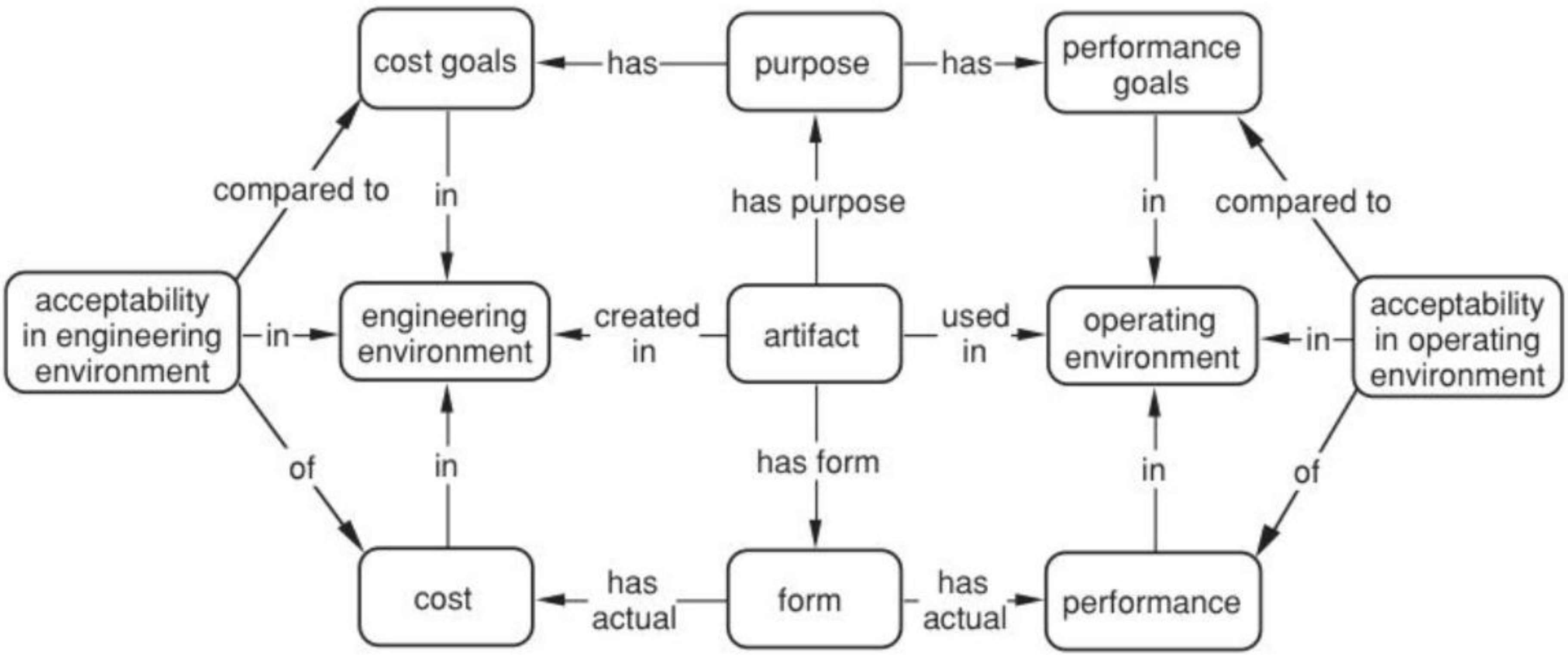
Forces in the operating environment drive the form of the design so that its actual performance acceptably serves its purpose, while forces in the engineering environment drive the form in a direction that keeps its development cost within available resources. Together, these forces "squeeze" the design into its final "shape."



Requirements, Specifications, and the Forces That Shape a Design

- For an engineer to produce an acceptable design:
  - Must be able to determine how much and in which direction to change each aspect of the form in order to make it acceptable.
  - This requires that the actual performance and performance goals, as well as the actual cost and cost goals, be expressed as quantities that can be objectively measured and compared.

Requirements, Specifications, and the Forces That Shape a Design



Constraints and Objectives

- Engineers express goals in two common ways:

- Constraints or,
- Objectives.

Constraints and Objectives

- A constraint is a hard limit on a value, typically expressed as a mathematical inequality or equality.

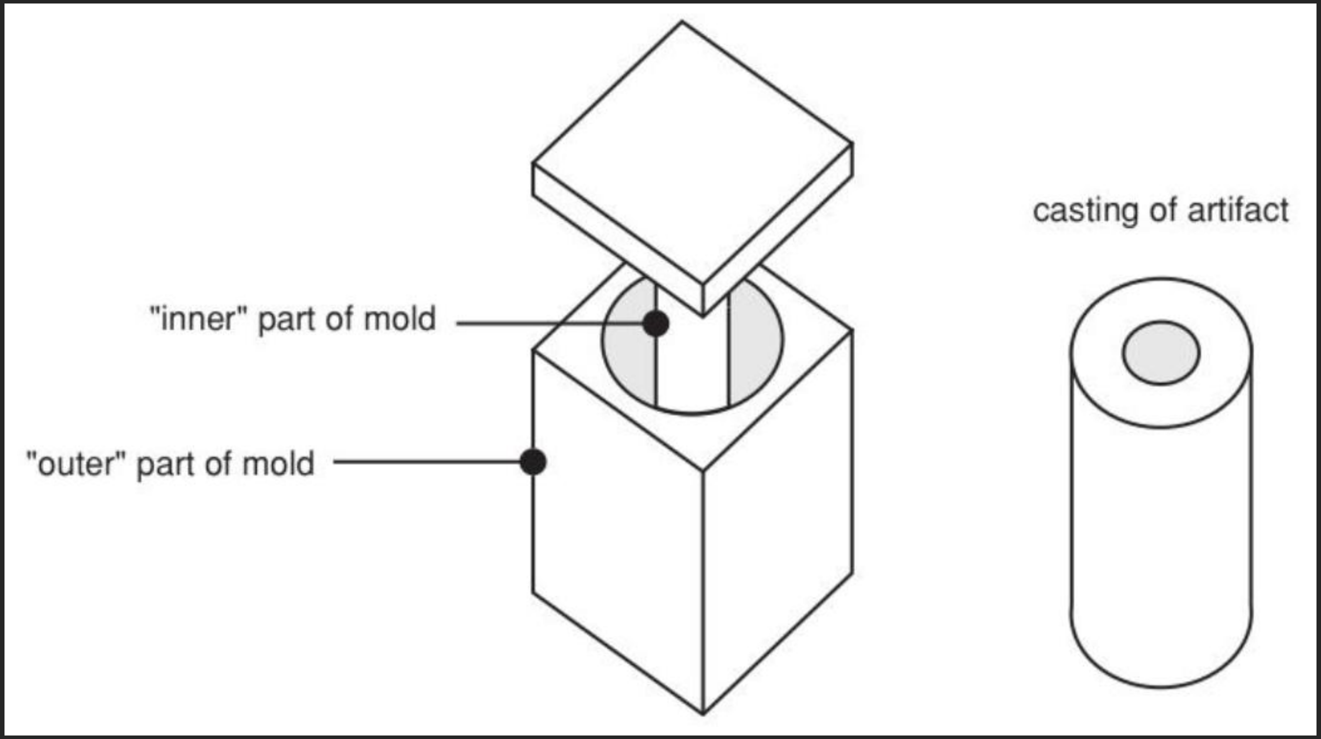
- Some examples of constraints in the specification of a watch include:
  - it's accurate to within ± 15 seconds per month
  - it's water-resistant to a depth of up to 30 m
  - its battery life is at least 2 years

Constraints and Objectives

- An objective is a goal of minimizing or maximizing a value.
- The main difference between a constraint and an objective is that while a violation of a constraint makes the artifact unacceptable, an objective indicates a direction for a performance to make the artifact more or less desirable.
- We may also consider an objective a "soft constraint" that's desirable but not critical to meet.
- Some examples of objectives for the design of a watch include:
  - its design should seek to minimize the manufacturing cost, and
  - it should be as thin as possible.

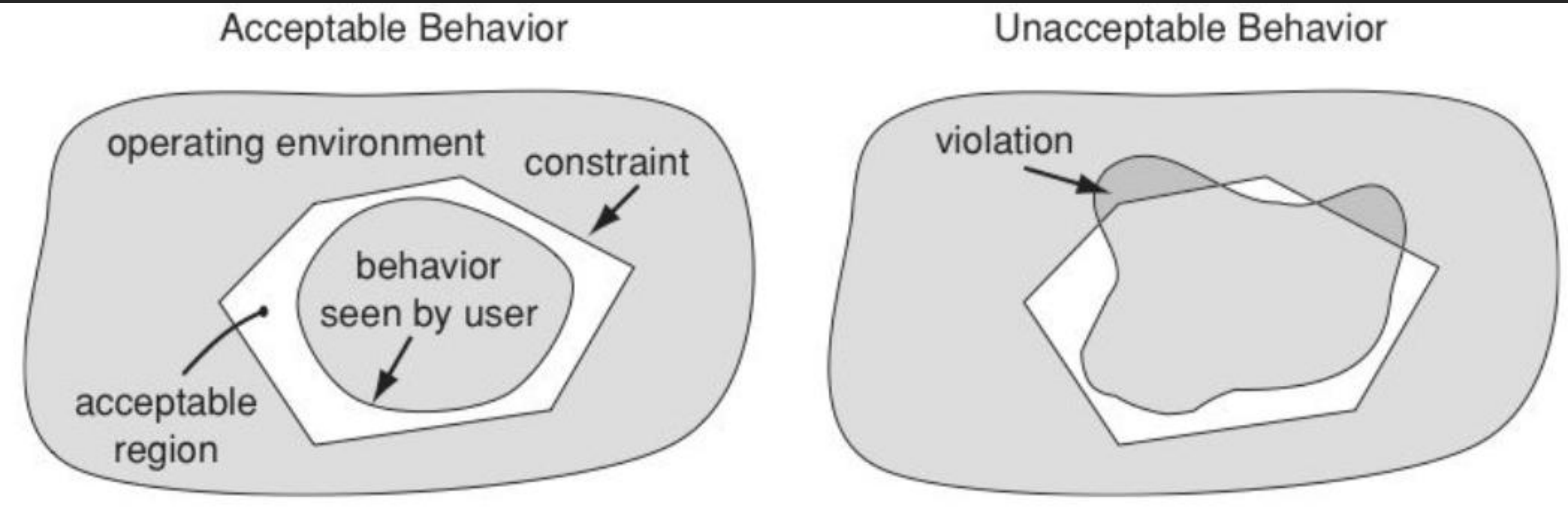
The Environment as a Mold for a Design

- The environment can be thought of as a mold for a design



The Environment as a Mold for a Design

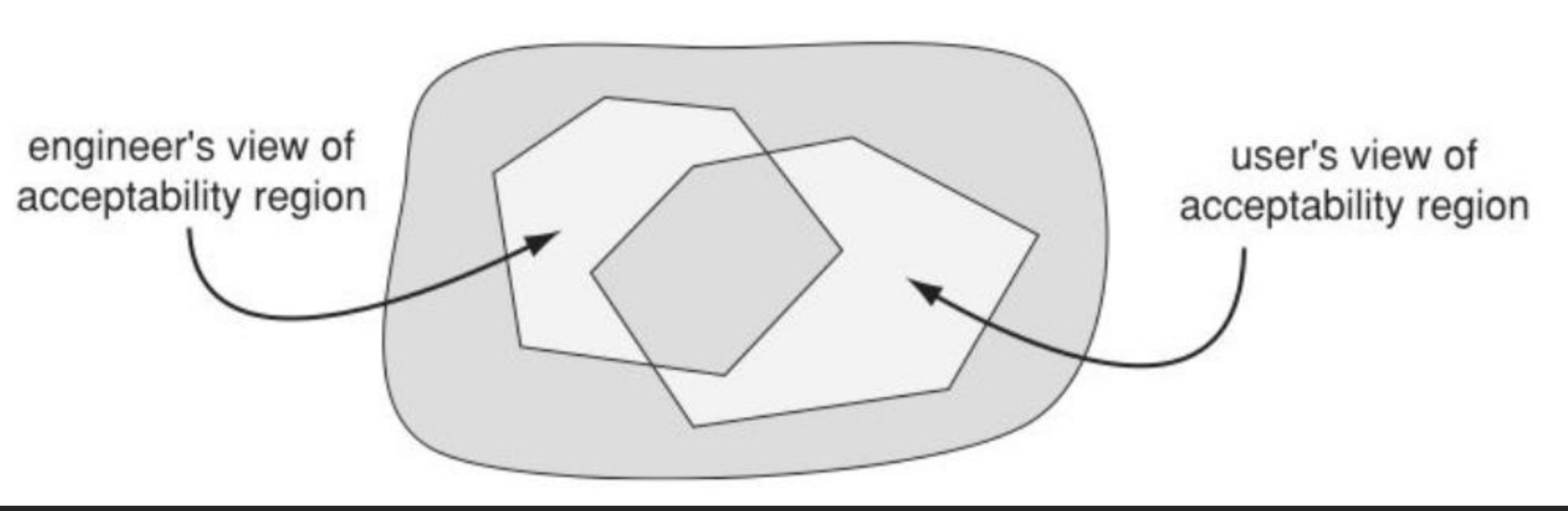
- If we think about this analogy carefully we can create a mental image that gives us greater insight into the relationship among purpose, environment, and form.



The operating environment is the outer environment

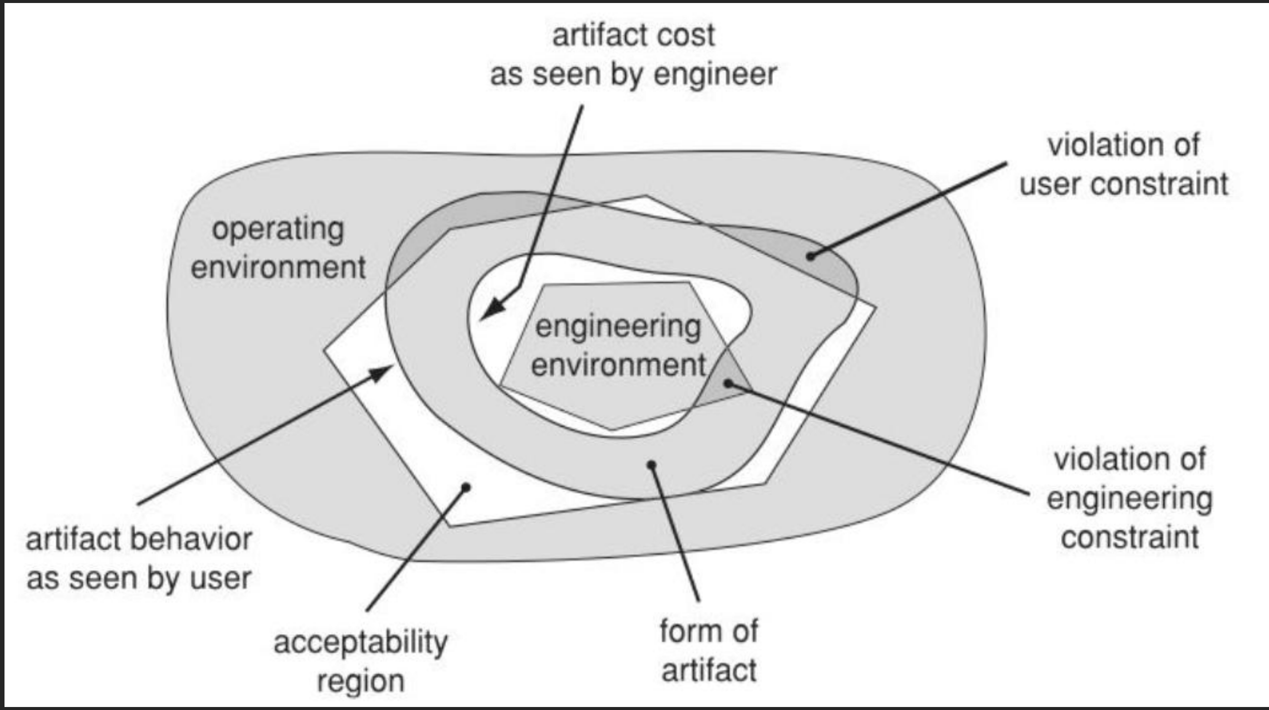
The Environment as a Mold for a Design

- Engineering projects fail when engineers either misunderstand the purpose of an artifact from the user's perspective, or overlook some aspect of the operating environment. In either case, the effect is the same—the engineers miscalculate the location of the acceptability region.



The Environment as a Mold for a Design

- Just as the operating environment can the thought of as the outer environment, the engineering environment can be though of as the inner environment.



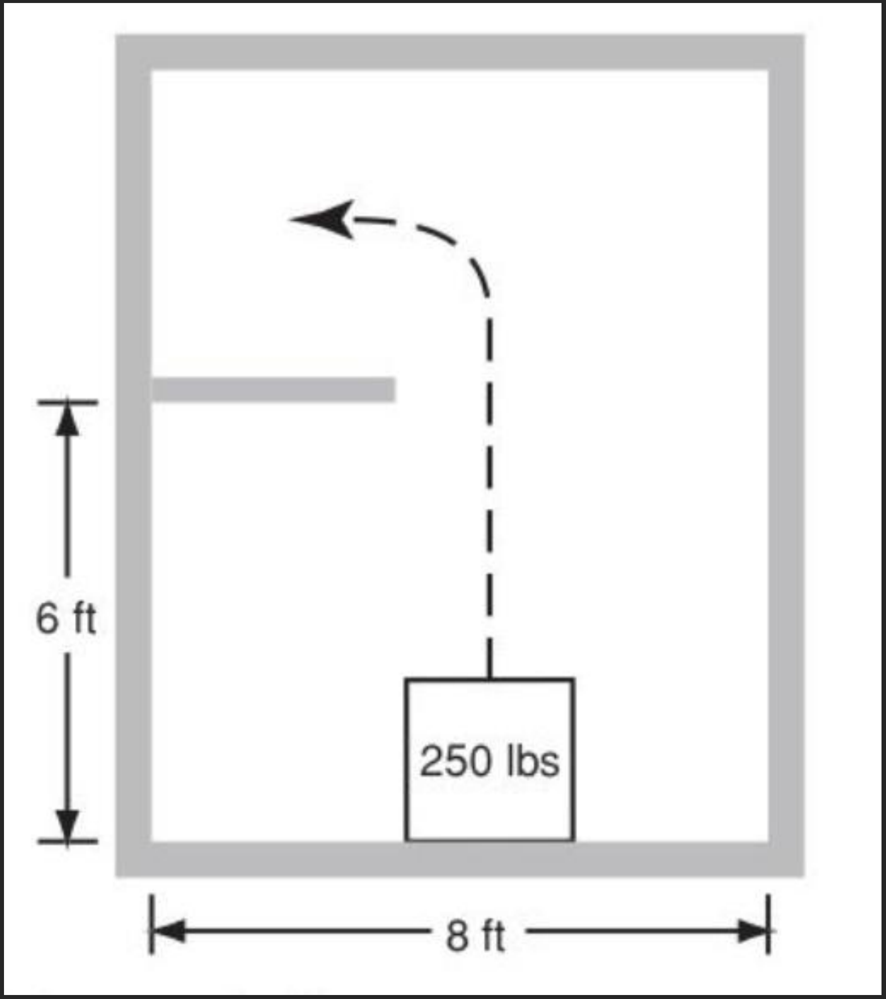
The constraints imposed by the engineering environment limit the cost of the design, as measured in monetary, time, or other units. Simon refers to the engineering environment as the inner environment of an artifact—in other words, this environment holds the resources within the control of the engineering organization.

Design Hierarchies

- We will now consider the form of an artifact.
- We will look at how we can break down a design problem into a hierarchy of subordinate problems and how engineers use both composition or parts hierarchies, and abstraction or classification hierarchies to synthesize a solution.

Design Hierarchies

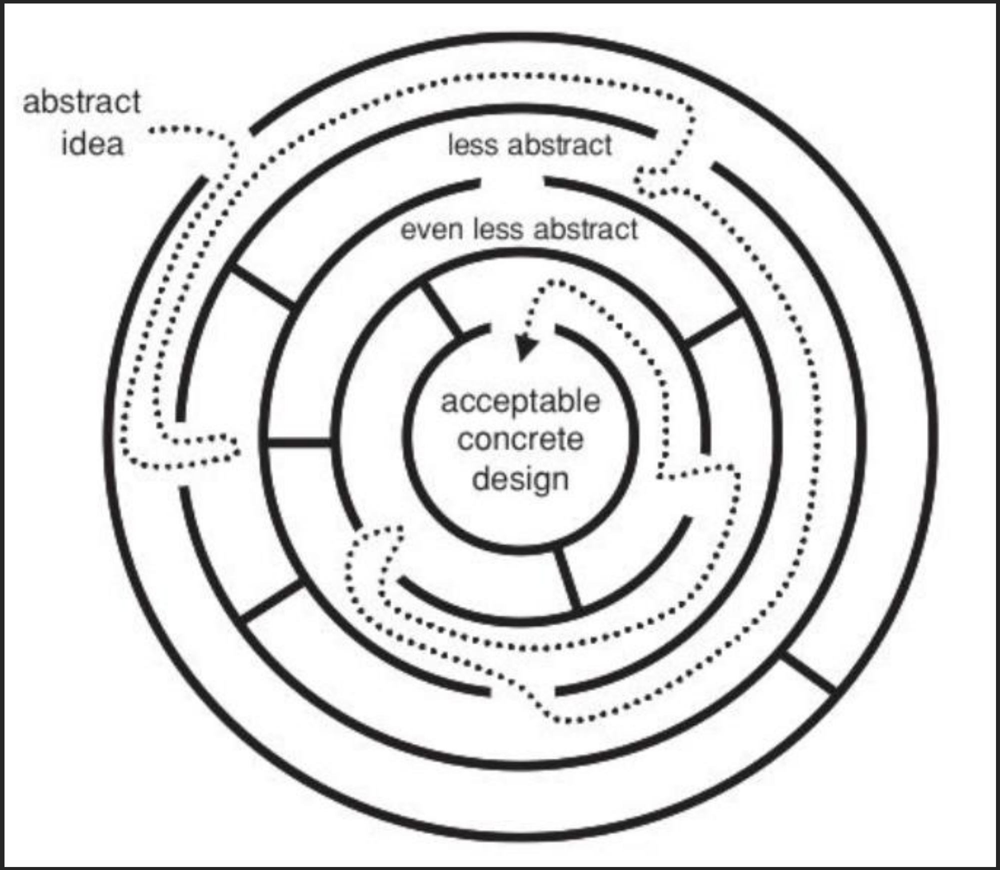
- Our Problem:
- Design a system for a 125 lb person to lift a 250 lb weight from the floor and place it on a shelf 6 ft high in a closet 8 ft wide by 8 ft deep.



Design Hierarchies

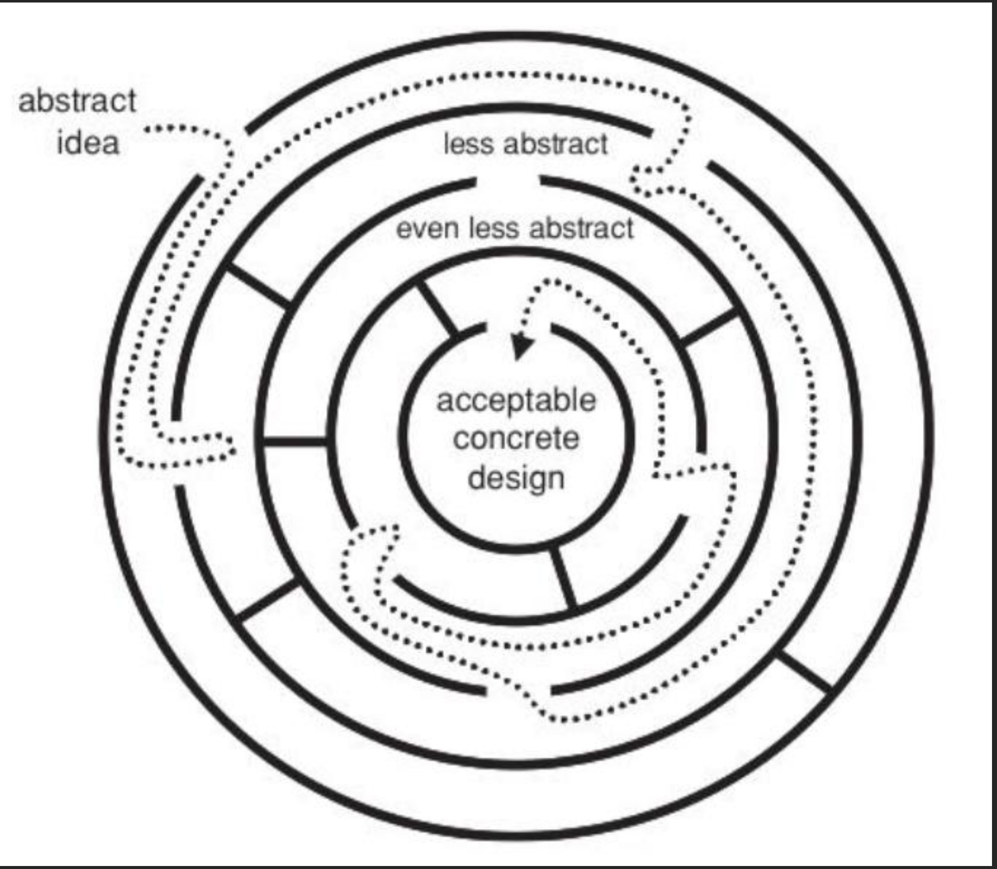
- While you may already have many ideas let's do this systematically.

- We can compare the design process to finding a path through a maze. Engineers rarely solve a problem all at once.



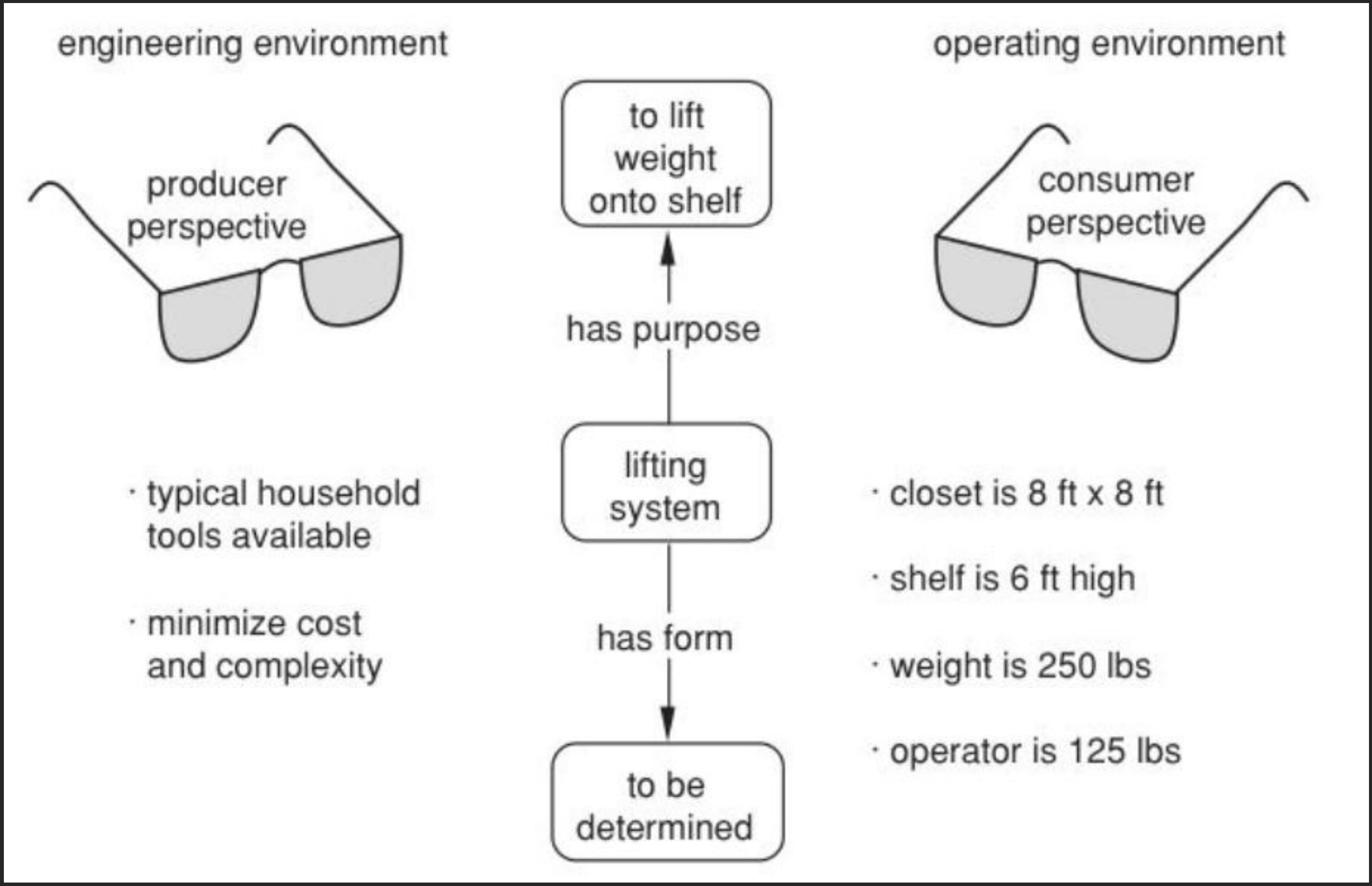
Design Hierarchies

As the designer advances through each ring of the maze, he determines more of the unknowns and the design gradually transforms from an abstract concept to a concrete implementation. The first few passes, or the outermost rings in the Figure, are sometimes called conceptual design, while the later passes or innermost rings are called detailed design.



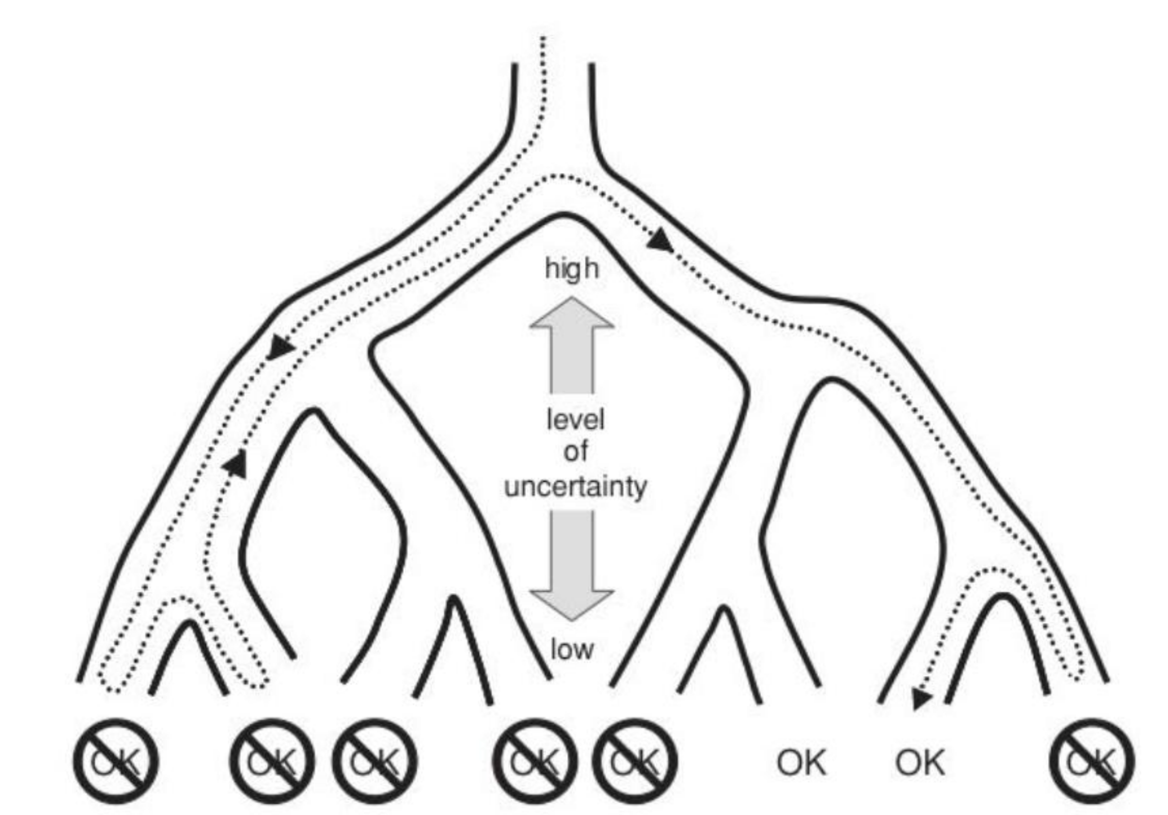
Design Hierarchies

Concept map for the lifting problem showing goals and constraints in the operating and engineering environments



Design Hierarchies

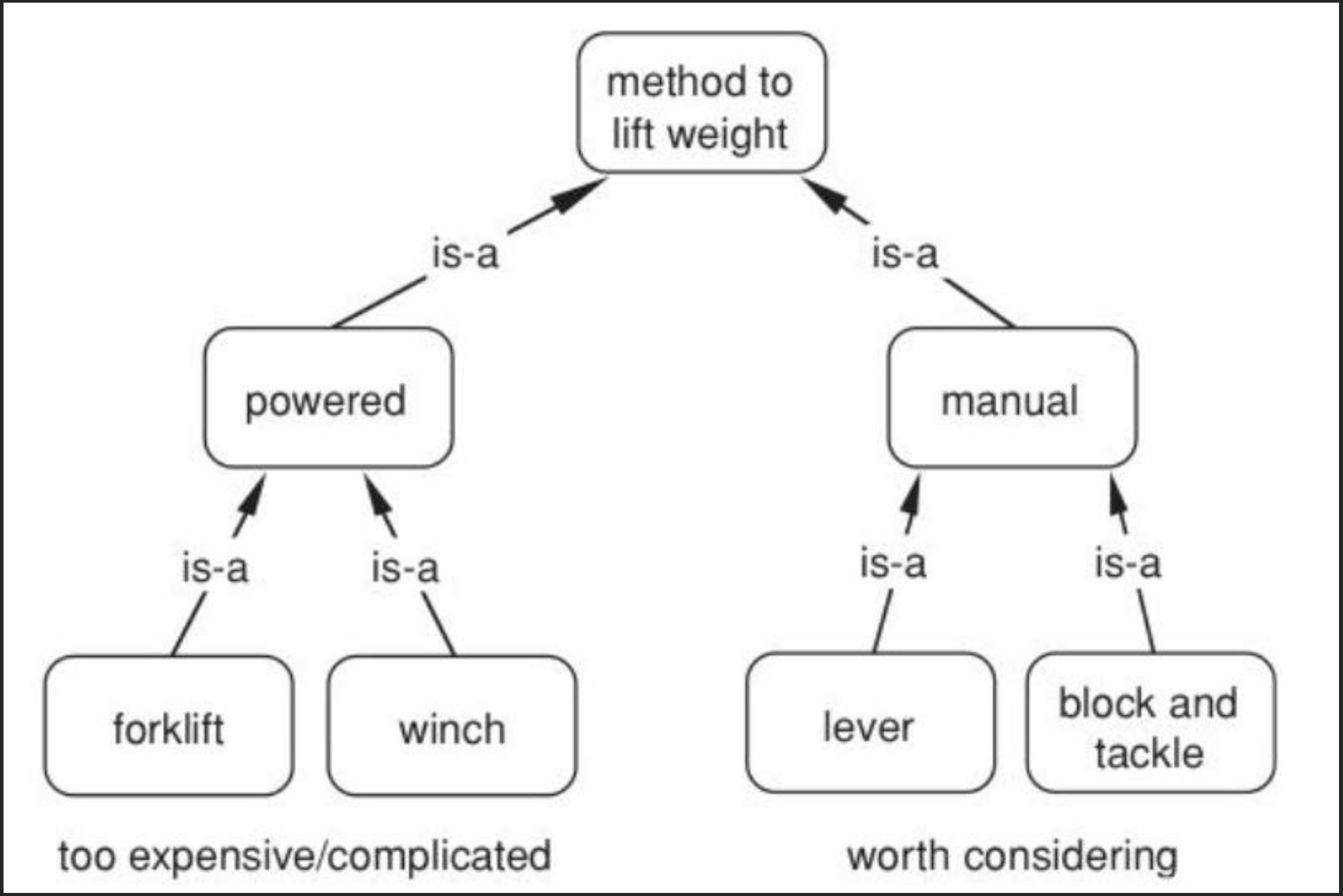
- As a designer searches for a path from the initial problem statement to a final, concrete design, he or she faces a series of decisions, where each decision pins down some aspect of the design and also limits choices later on. We can picture this process as finding a path through a set of branching roadways



This hierarchy of choices is called a decision hierarchy or decision tree.

Design Hierarchies

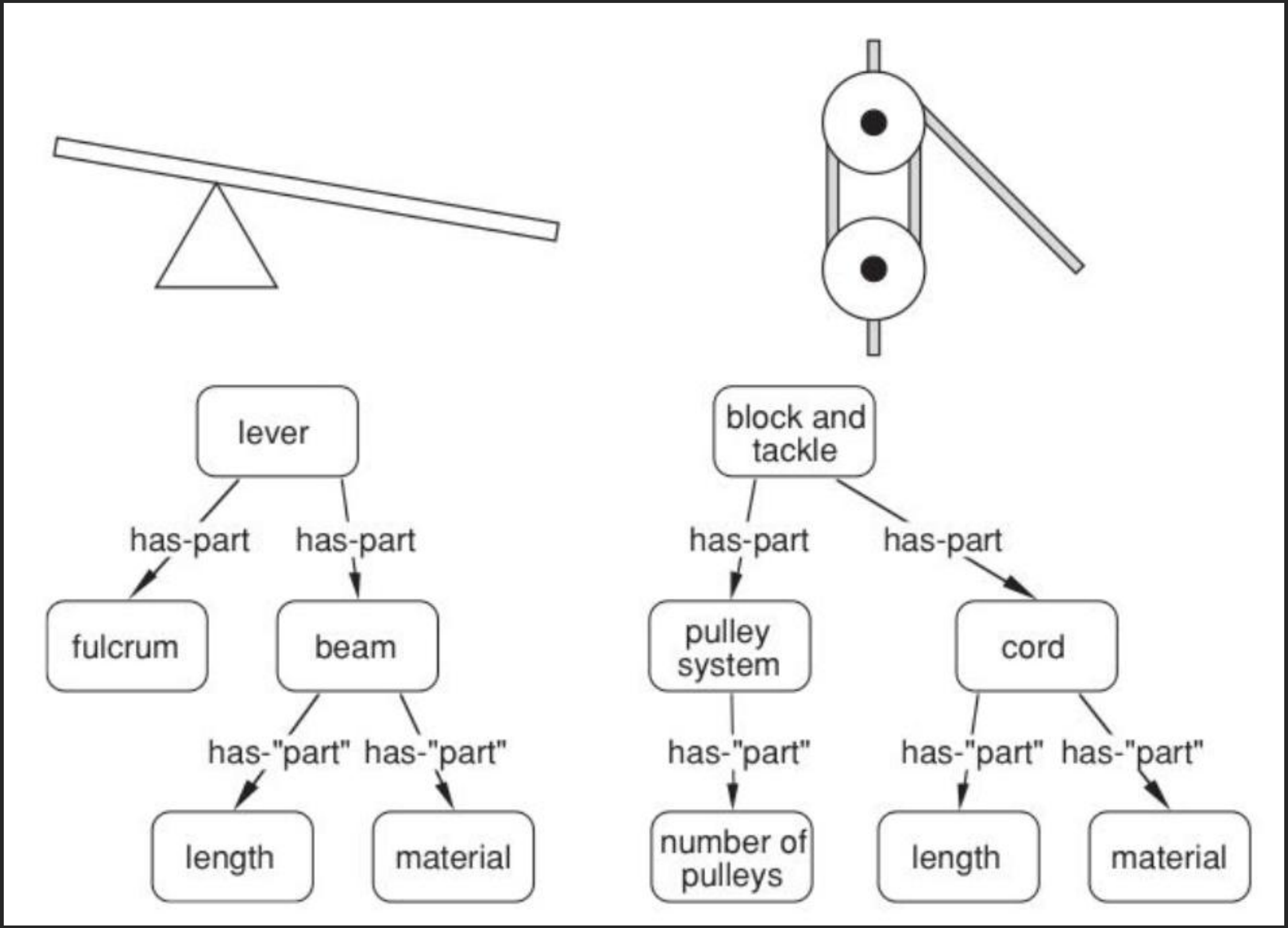
- A class hierarchy for lifting weights.



Structural Hierarchy

- For our manual method we could use a lever system or a block and tackle.
- We need more detail on these two methods and one way of doing this would be by structural hierarchy, a kind of composition hierarchy.
- Higher-level nodes are connected to the lower-level nodes through "has-part" relationships.

Structural Hierarchy



Structural hierarchy of the two lifting methods

Structural Hierarchy

- Each of these we can further break down to unveil more design questions.

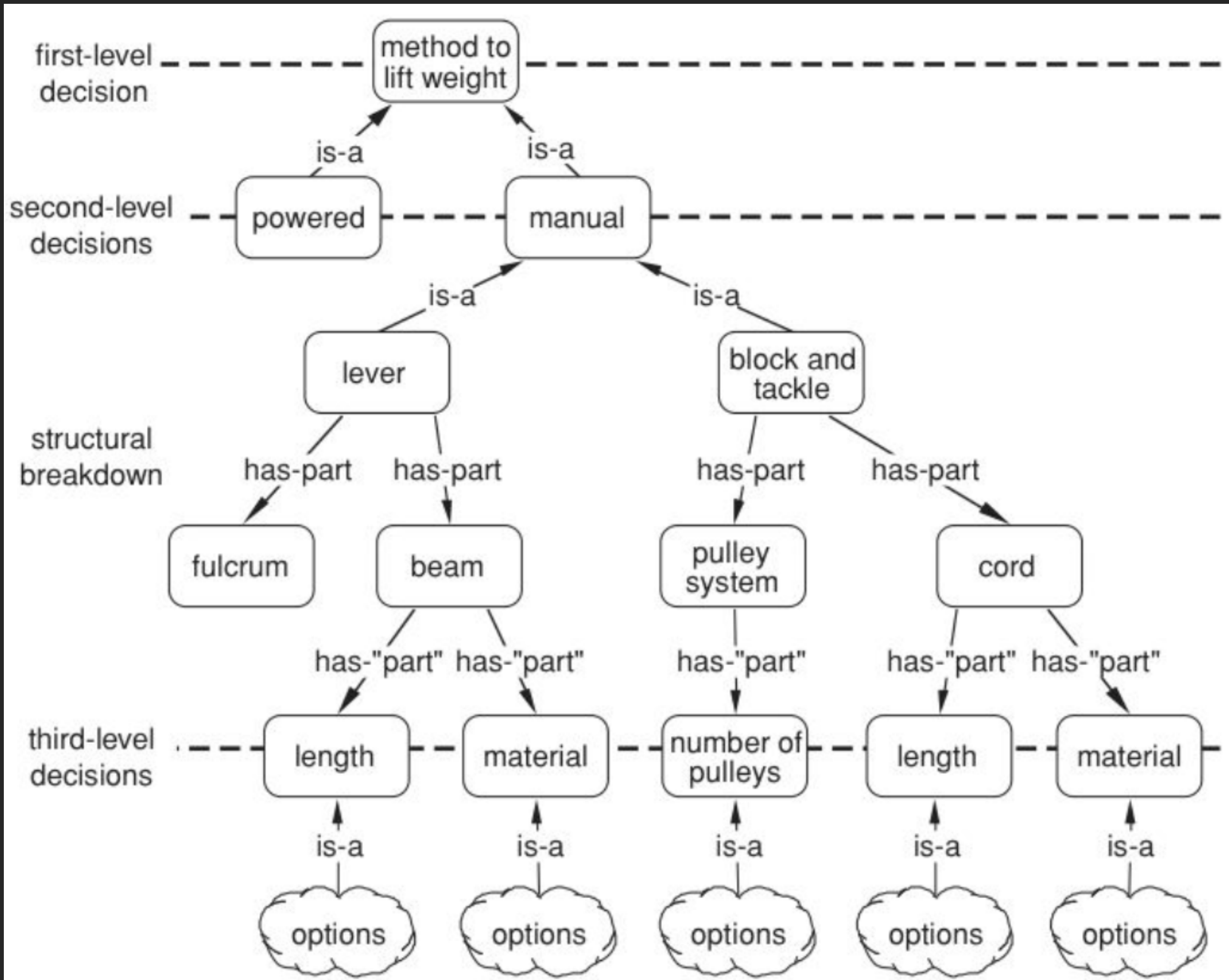
- The "parts" in the second level of the structural breakdown are not physical components, but rather parts of the remaining information we need to specify remaining details of the design.

- These include details such as the length and material of the beam of the lever, or the number of pulleys and type of cord for the block-and-tackle.

Searching the Design Space

- We can combine aspects of both a decision tree and a structural hierarchy into a single concept map that gives a comprehensive picture of the space of possible solutions.

- The diagram contains three levels of decisions:
  - The first level chooses between powered and manual methods;
  - The second level selects between a lever and a block-and-tackle as two different manual methods; and
  - The third level involves design choices specific to either the lever or block-and- tackle.



A concept map that uses a combination of a decision hierarchy ("is-a") relationships and a component hierarchy ("has-part" relationships) to illustrate the options for manual methods for lifting a weight.

Searching the Design Space

- Remember, we don't jump to the final design we just saw all at once.
- We could approach this from top-down, bottom-up, or from middle outwards.
- In addition to moving up or down, we could work left or right.

Searching the Design Space

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Searching the Design Space

- There's also the choice of exploring paths in a depth-first or breadth-first order.

- In a depth-first search, you'd follow a path from the root of the tree to a leaf, and then evaluate whether the design at the end of the road is acceptable. If it isn't then you'd retrace your steps and explore another path to a leaf.

Searching the Design Space

- In a breadth-first search, you'd move slightly down each path at a given fork in the road, and explore the full breadth of options at each level, and then decide which looks most promising.

- In other words, in a breadth-first search you spend extra time to observe each pathway, whereas the depth-first approach follows a path without interruption.

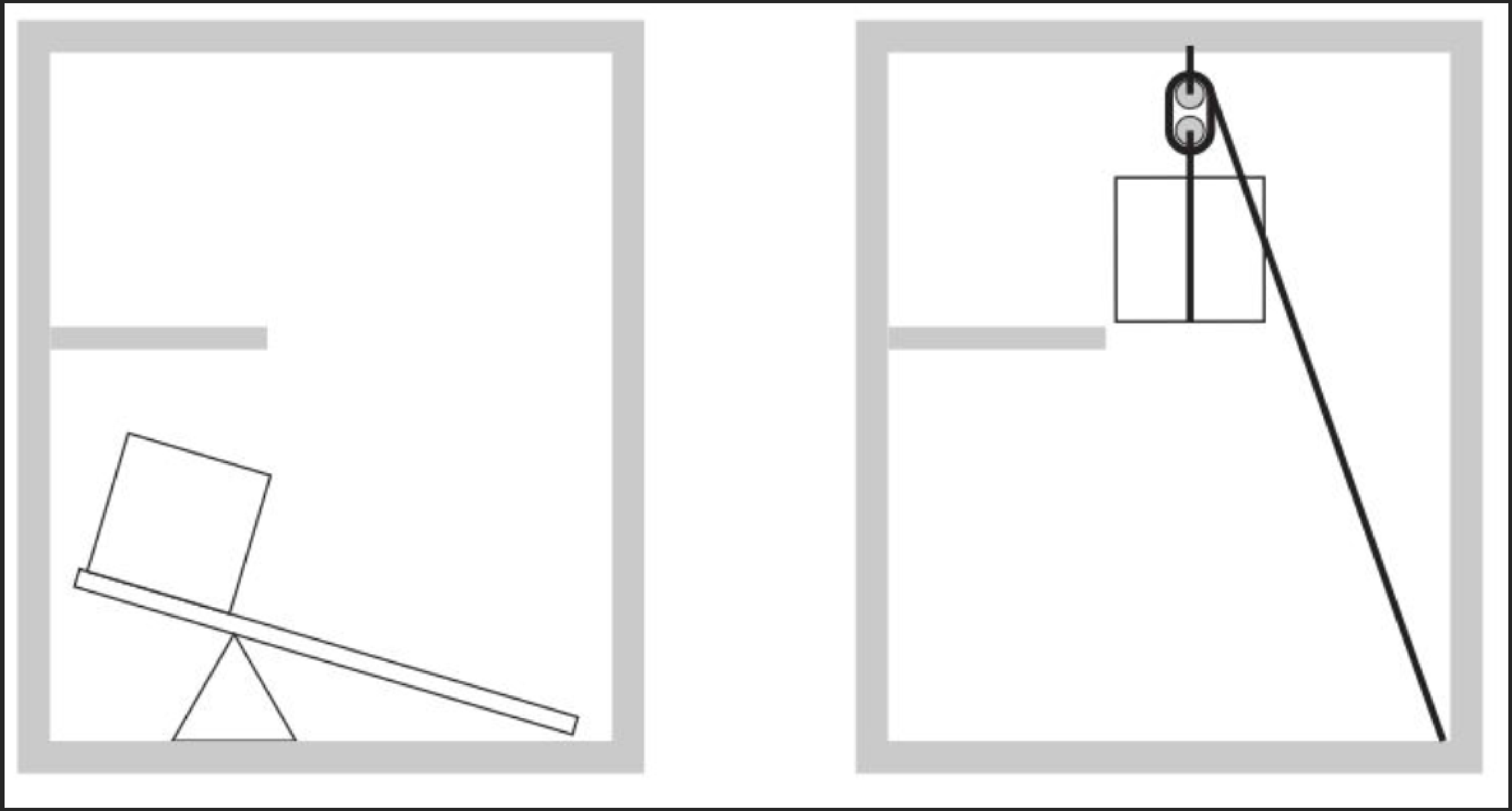
- Clearly, a breadth- first approach can save wasted time and effort, but sometimes it's impossible to determine the most promising path without proceeding slightly down toward the end.

Searching the Design Space

- Despite how you may approach this, sometimes a given path does not yield an acceptable solution in terms of:

- Operational environment
- Engineering environment

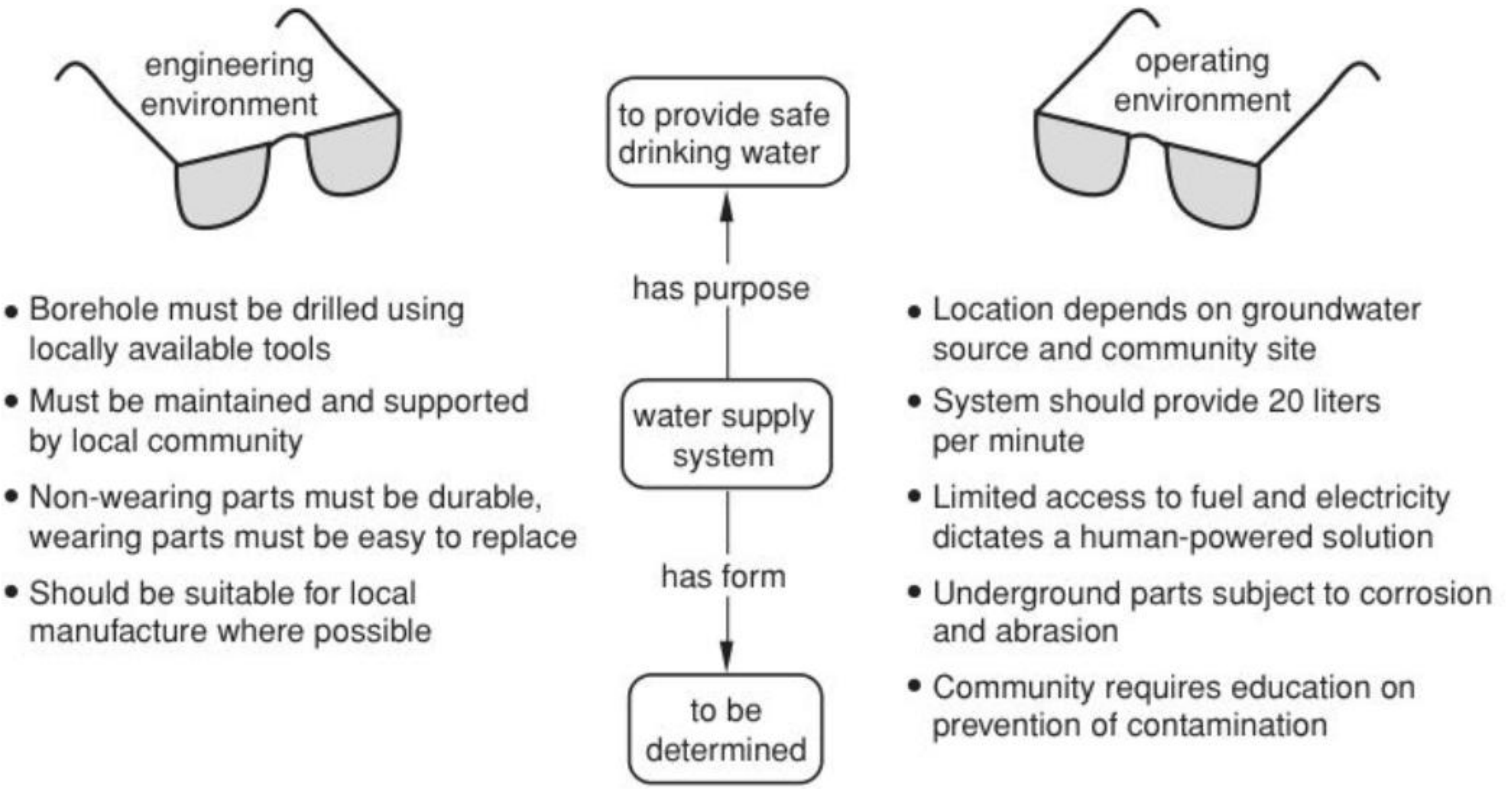
Searching the Design Space



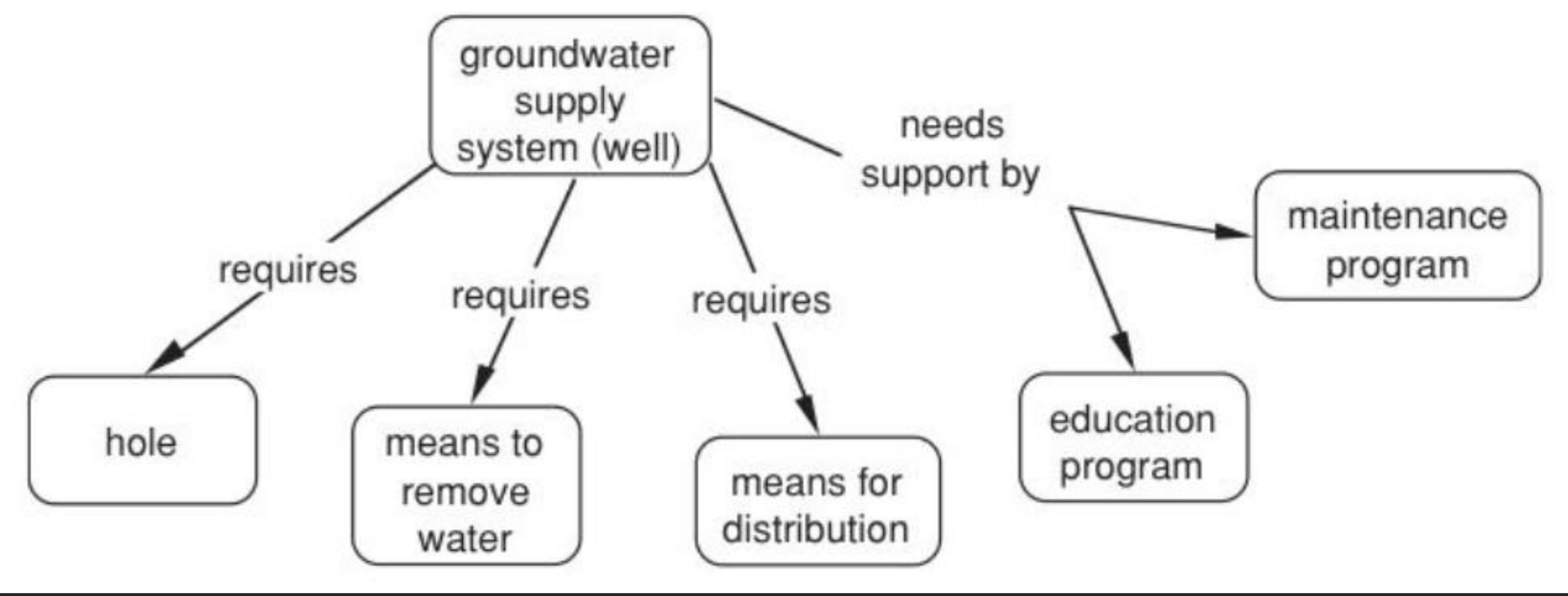
There is no feasible solution for using a lever to lift the weight to the required height in a small room, while there does exist a solution using a block and tackle.

See Example of Water Supplies for Rural Communities in Developing Nations

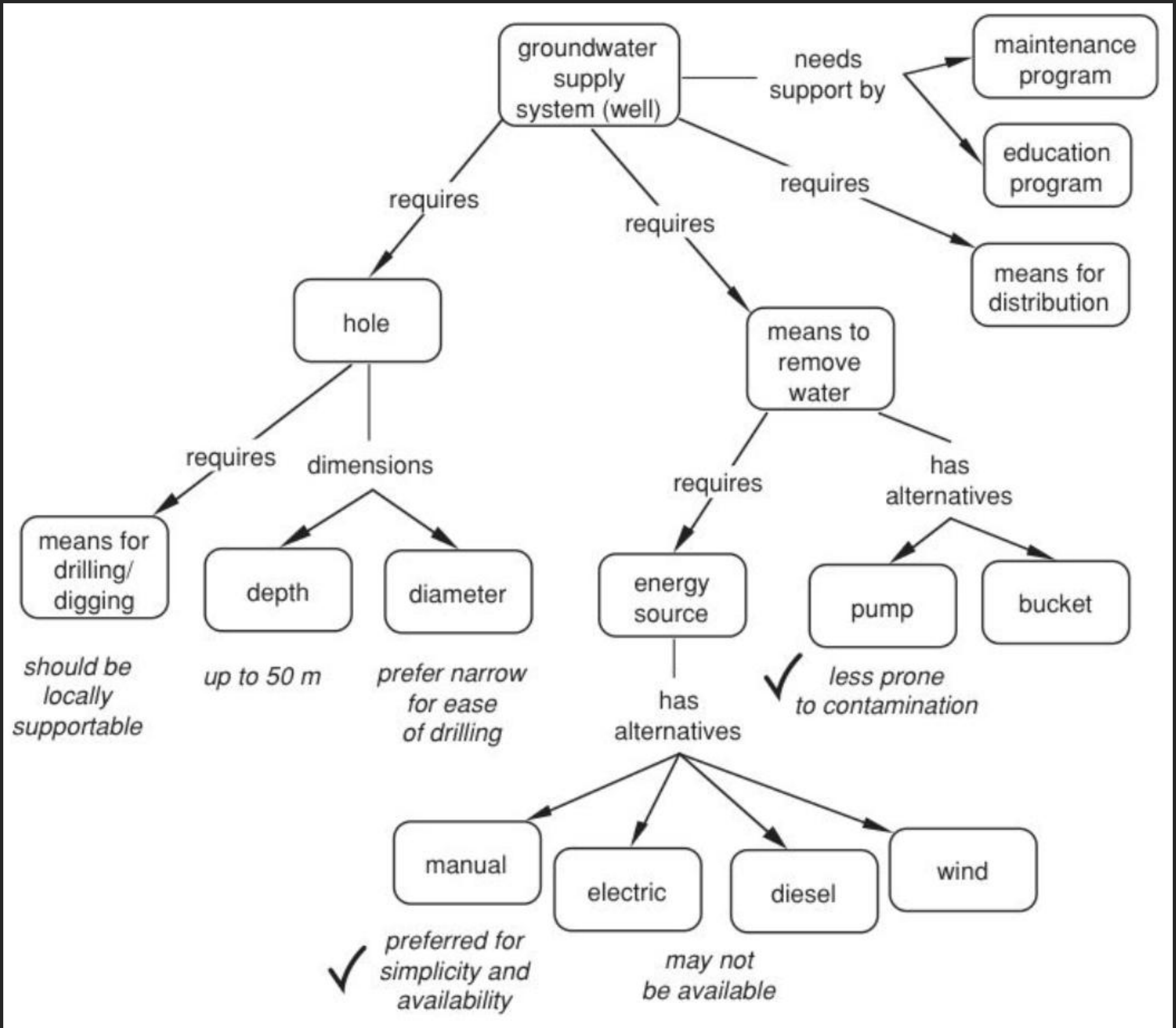
Top Level Problem: Meet Community Needs



Top Level Components



More Detail


groundwater supply system (well)
needs support by
maintenance program
education program
requires
means for distribution
requires
means to remove water
requires
hole
requires
dimensions
means for drilling/ digging
depth
diameter
should be locally supportable
up to 50 m
prefer narrow for ease of drilling
requires
energy source
has alternatives
pump
bucket
less prone to contamination
has alternatives
manual
electric
diesel
wind
preferred for simplicity and availability
may not be available

See Lower Level Components In Book

Hand Pump Design
Bearings and Seals