Introduction to Cybernetics and the Design of Systems

Collected Models
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Hugh Dubberly
Paul Pangaro

As observers, we say that certain systems are organized to act effectively in their environment in order to achieve a goal. To do so, a system must be able to sense its environment, compare what it senses (current state) to a model of its goal (desired state), and to act in a manner that moves closer to its goal.

In general terms, a system experiences disturbances from its environment that move it away from its goal. The system must be able to respond so that it can achieve its goal despite the disturbance.

Essential variables are those parameters of a system's operation that must be kept within strict limits for the system to achieve its goal. The alternative is a system that is ineffective at achieving its goal, or even dying or being destroyed.

In the case of a thermostat, the essential variable is the temperature of the room; if kept close to the setpoint of, say, 70° F, we say the system has maintained its essential variable.

The capabilities and capacities of a system to overcome disturbances and to achieve its goal must be measurable, if design is to be explicit. Of course, it is always possible to try more-or-less random changes until something works. This wastes resources by "just trying things" instead of converging efficiently and purposefully. In addition, such random attempts increase the risk of system failure between now and (possibly never-attained) success.

One way to measure a system's capabilities is in terms of the number of different possible responses that the system, because of its make-up, can have to what it senses in the environment. In the case of a simple thermostat, the system has 2 possible responses: turning the heater on or turning it off.

Using a number to reflect range of capabilities of a system is particularly mechanistic and or quantitative, but valuable as a starting point.

We call the range of possible responses embodied in a system its variety. In the course of many design tasks—software or service design, for example—a simple numeric measure of the total number of responses may seem too simplistic. But there is great value in thinking about—and explicitly designing for—the variety of the systems we create and then evolve. Just as the scope of cybernetics extends from mechanical to biological to social systems, so does the concept of variety.

If a system possesses enough variety to achieve its goal, we say the system has requisite variety (RV), that is, it has the variety required to succeed in achieving its goal.

For a system to have requisite variety, the system must possess at least as much variety as the environment that is the source of the disturbances. This is called Ashby's Law of Requisite Variety

RV is always a relationship between a system and a proposed environment. While the system's variety changes only when the system is changed, RV is judged to be present or not depending on a comparison between a measure of system variety and a measure of the variety of an expected environment.

It is incorrect to refer to "adding to a system's requisite variety" or "giving the system more requisite variety". Either the system has RV or doesn't; it is a binary relationship between system and environment, not a quantity.

Introduction to Cybernetics
and the Design of Systems

Requisite Variety

Requisite Variety

origins

a. individuals
W. Ross Ashby

b. era/dates
Early 1950s

c. references for model, context, author(s), concepts
Design for a Brain (1952) and Introduction to Cybernetics (1956),

Introduction to Cybernetics is available for download at http://pespmc1.vub.ac.be/ASHBBOOK.html.

See also Geoghegan and Pangaro, "Design for a Self-Regenerating Organization", that applies Requisite Variety to social organizations, available for download at http://pangaro.com/ashby.

d. examples
A pilot + ship's ability to withstand a storm. A heating system's ability to keep the internal temperature above 70° F during a cold snap. A corporation's ability to avoid bankruptcy during a market downturn.

a. goal of model
"Variety" is the measure of a range of behaviors, whether the system's or the environment's. Ashby rigorously explicates the limits of a system's ability to achieve its goals with his concept of "Requisite Variety".

b. description
The term "control" applied to a system's relationship to its environment is potentially confusing: while some systems can, in practice, dominate their environment (for example, a human's relationship to a pencil), it is almost inevitable that disturbances (whether predictable or unforeseen) arise to confound the system. What can be done? Designers can calculate variety in the system and the environment, and decide on trade-offs of viability and cost.

c. components and processes
Ashby coined the term "Essential Variables" to refer to those aspects of a system that must be maintained within a specified range in order for the system to be viable, that is, to continue to exist as the system in question. Text at right explains the relationship among these terms. The diagram under "Result = EV Preserved" shows metaphorically that the system's variety in all cases meets the variety of the environment, and so persists. Under "Result = EV Destroyed", the system cannot respond to particular disturbances in the environment—as indicated by "?"—and so cannot persist.

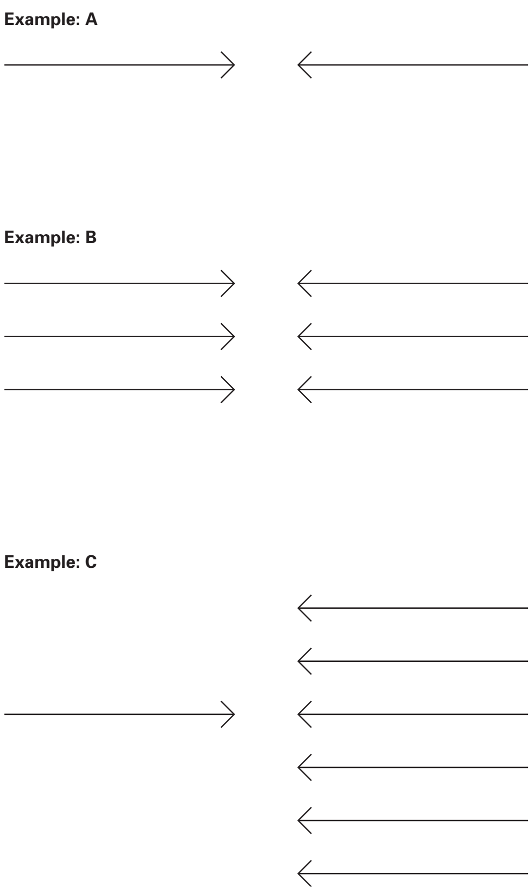
d. important aspects of model/breakthrough
For the first time, Ashby provides a tool for determining viability of a given system design.

Requisite Variety

A regulator achieves a goal (preserves an essential variable) against a set of disturbances. To succeed, variety in the regulator must be equal to or greater than the variety of disturbances threatening the system. If this is so, then we say the system has requisite variety.

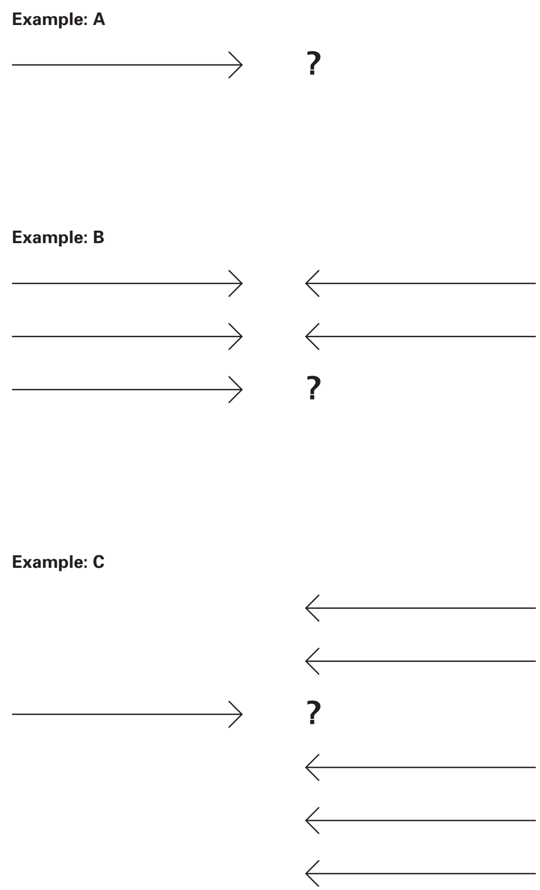
Result = EV Preserved
(system succeeds—“lives”)

Variety in Disturbance | Variety in Response



Result = EV Destroyed
(system fails—“dies”)

Variety in Disturbance | Variety in Response



Requisite Variety is a Function of the System's Goal

a. goal of model
The diagram contrasts the probability of a disturbance occurring with the cost of constructing a system that will successfully regulate against that disturbance. It also shows variety as a quantity, rather than a discrete conditions that are present or not-present, as in prior diagrams.

b. description
Extending the range of a system's viability is not without a price: in general, the more extreme a disturbance, the greater the effort required to counter it. In turn, more resources are required to construct, comprise, or operate the system under those extreme conditions; and, in turn again, the greater the cost of handling those extremes.

c. components and processes
Looking bottom to top, the left-hand figure shows the value of an essential variable (e.g., temperature) from cold to hot (shown bottom to top). The curve shows that the probability of extreme cold is low (bottom); the probability of middle-level temperatures is greater; and the probability is again low for the extreme hot (top).

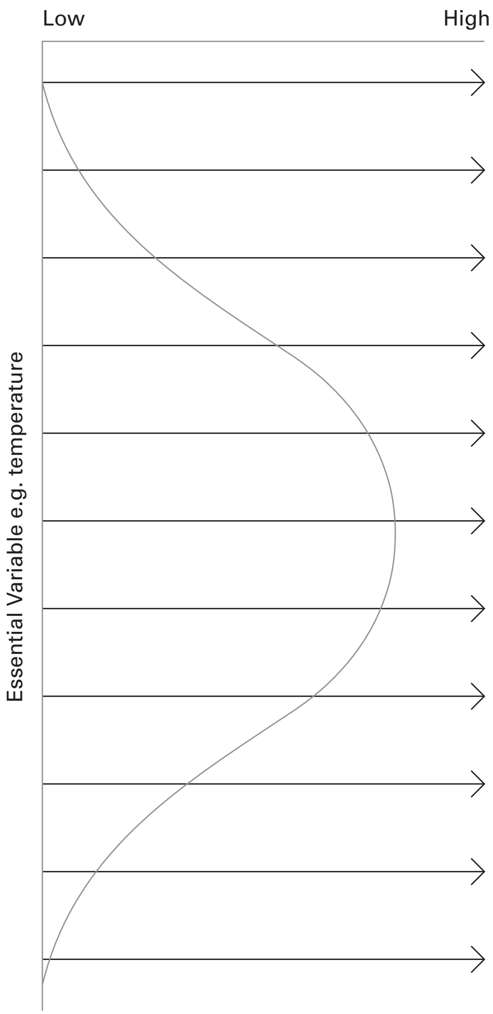
The right-hand figure shows, for the same range of temperatures bottom to top, that the cost of attaining the goal goes from high, at the extremes, to low in the middle values. The size of the area to the right of the curve is a rough indication of the cost of constructing and/or operating a system to handle the range of disturbances.

d. important aspects of model/breakthrough
Although not quantitatively precise, the diagram displays the consequences of design decisions in terms of variety versus cost.

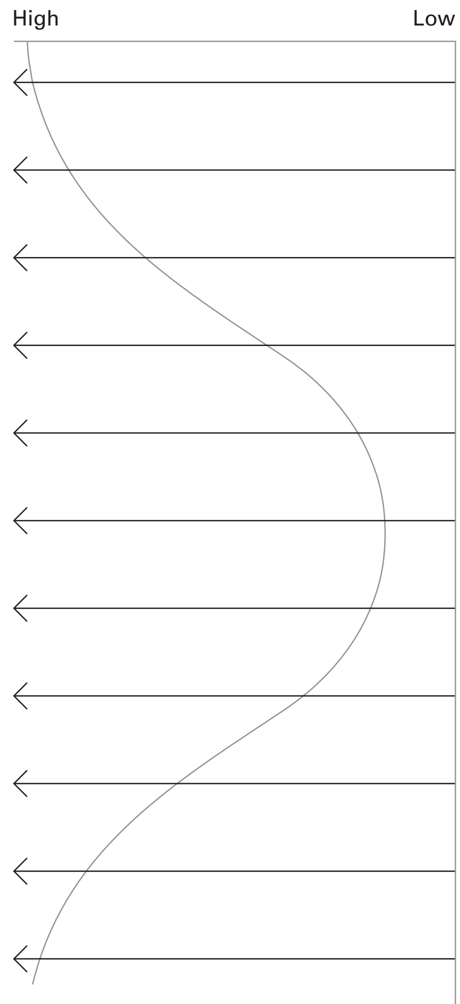
Requisite Variety is a Function of the System's Goal

Determining appropriate goals involves balancing
probability of disturbances against cost of meeting them.

Probability of Disturbances



Cost of Attaining Goal
(Goal responds to a range
of disturbances)



The greater the range of disturbances met—
that is the greater the variety of the system—
the more it costs.

Comparing the Cost of Adding Variety to the Probability of a Disturbance

a. goal of model
The graph provides another view of the relationship between variety and cost (can be compared to previous model).

b. description
Designers must be aware of the implication of the range of their design; specifically, that handling less-probable cases can increase costs significantly.

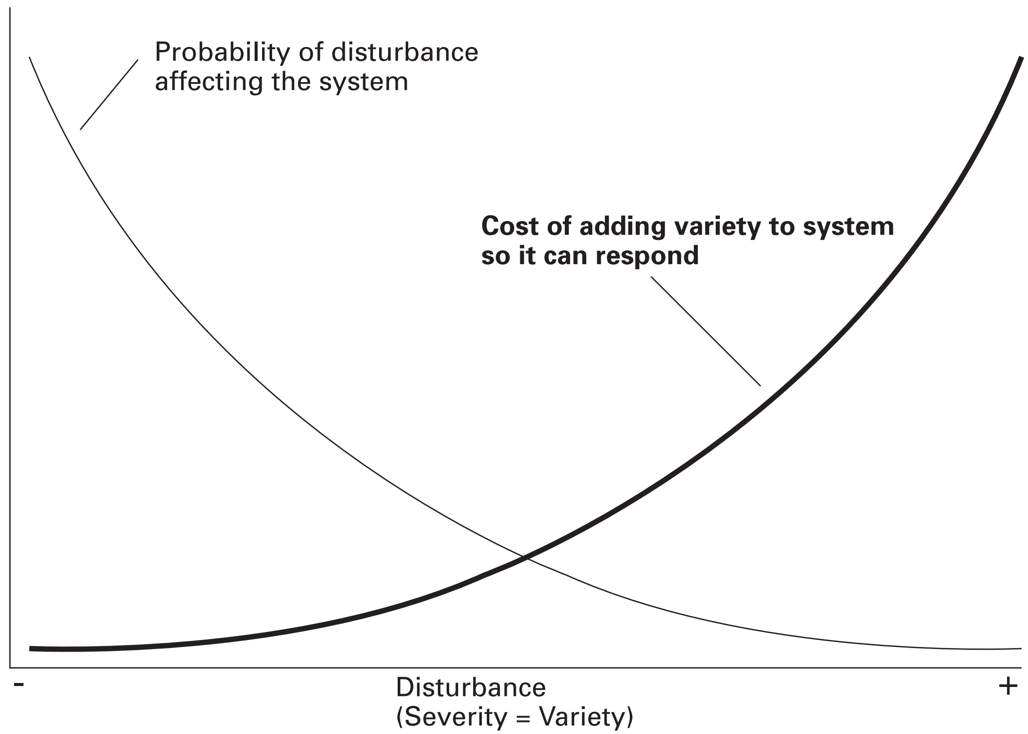
c. components and processes
The horizontal axis shows amount of Disturbance, with increasing disturbance from left to right. The amount of Disturbance, or its Severity, is another name for the Variety presented by the environment.

The vertical axis shows the probability of an environment exhibiting a particular degree of Disturbance.

The lighter curve shows that, as the Disturbance (Variety) increases, the probability of it occurring is reduced. The darker curve shows that, even as the probability of the severity of the Disturbance is reduced, the cost of handling it increases.

d. important aspects of model/breakthrough
There are always trade-offs in incorporating additional system complexity in service of system variety and the concomitant cost to achieve more system variety. This trade-off is one of the most difficult design issues in complex systems, and design outcomes may be improved by close examination involving multiple views and calculations

Comparing the Cost of Adding Variety to the Probability of a Disturbance



Requisite Variety: Formal Mechanism

a. goal of model
The diagram formalizes the required actions of the system to achieve requisite variety.

b. description
The diagram places the functioning of Requisite Variety in the frame of the formal model of a cybernetic system, as well as the Shannon model of a communication channel. Disturbances correspond to noise in Ashby, and Essential Variables correspond to messages in Shannon.

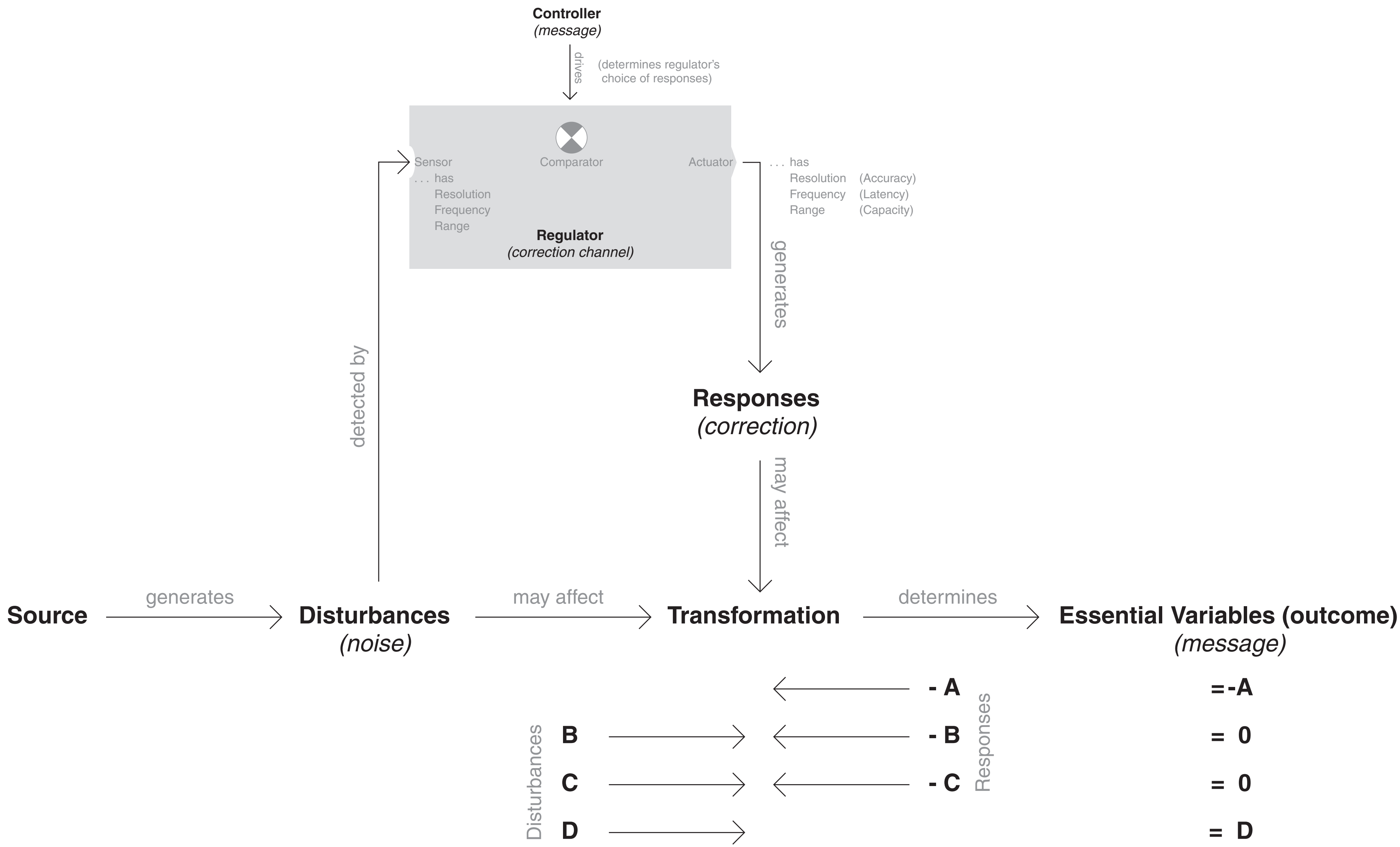
c. components and processes
Grey System Box: sensor, comparator and actuator operate as before. Note annotation of Resolution, Frequency, and Range as parameters on input and output; these become part of the design considerations in calculating Requisite Variety.

Channel Line: Source, Disturbances, and Transformation mirror Shannon’s transmission channel, used by Ashby to bridge the two models.

Lower Section: Arrows that show Disturbances meeting Responses, and calculation of Essential variables as per previous models.

d. important aspects of model/breakthrough
The diagram shows correspondences between Ashby’s and Shannon’s formulations.

Requisite Variety: Formal Mechanism



If variety of disturbances ⩽ the variety of responses, then the system remains stable (first 3 cases).
If variety of disturbances > the variety of responses, then the system becomes unstable (last case).

Requisite Variety Example: Space Heater

a. goal of model
This model results from the application of the previous model, the formal mechanism of requisite variety, to a space heater.

b. description
Each element of the model of requisite variety is mapped to the components of the system of a space heater.

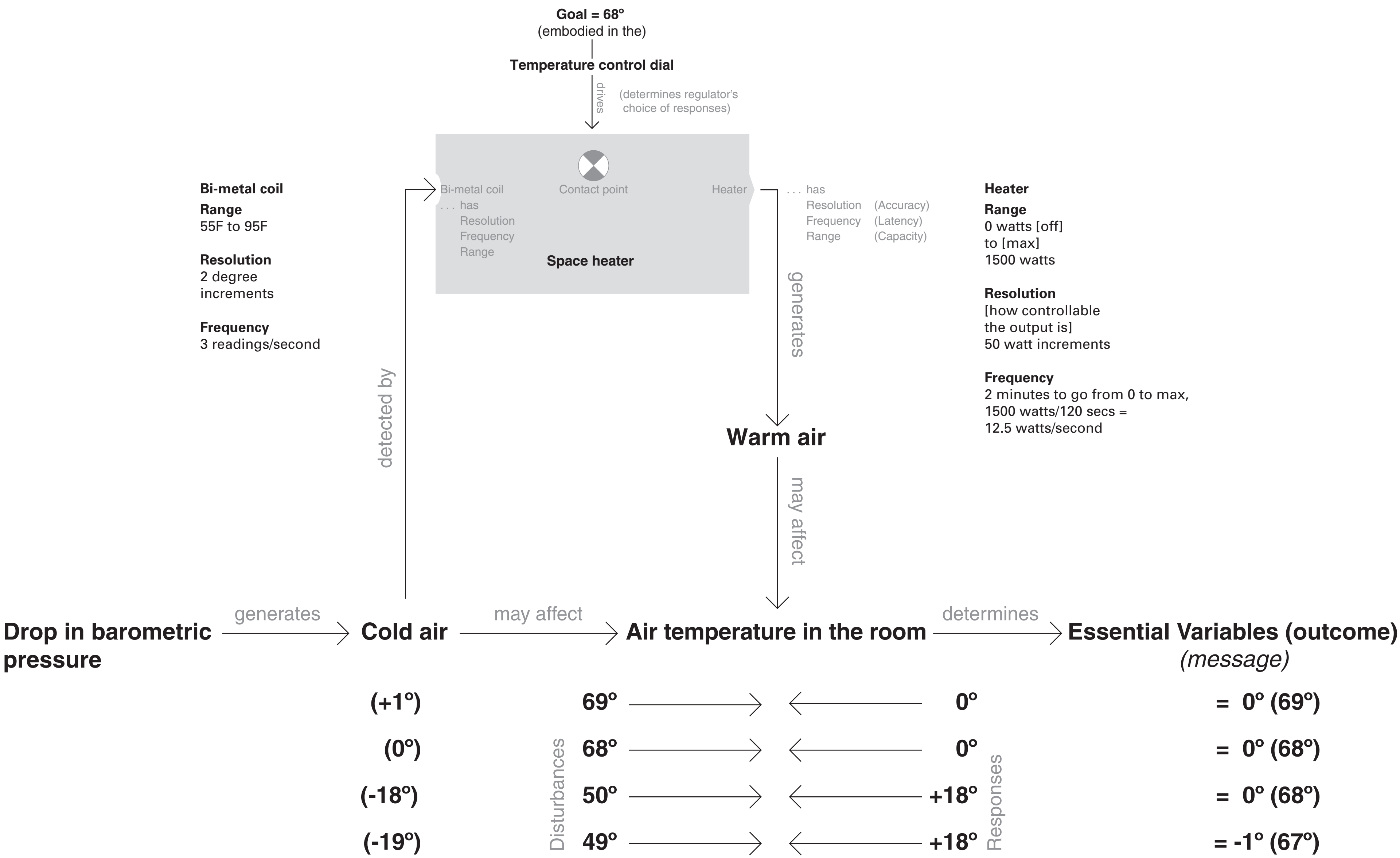
c. components and processes
Components and processes as per previous model. Specific values for variety of sensor and actuator are given. This enables a quantitative calculation of conditions for which the system is capable of maintaining the desired goal of 68° Farenheit. Note that 18° F is the maximum temperature shift possible with the current system design.

As shown in the arrowed-figure at bottom right, the system loses its ability to achieve its goal when the air temperature in the room goes from 50° to 49°. This is indicated by the Essential Variable moving to -1°.

d. important aspects of model/breakthrough
Not all variables under system control are necessarily, strictly 'Essential Variables' (EVs), that is, conditions required for the system to persist. Ross Ashby coined the term to refer to living systems, for which loss of control of EVs would mean, in the case of an organism, death.

Very often, as in the case of a space heater, subjecting the system to temperatures down to 40° will probably not damage it, even while it can't achieve its goal. However, subjecting the system to -20° probably would damage it.

Requisite Variety Example: Space Heater



If variety of disturbances ⩽ the variety of responses, then the system remains stable (first 3 cases).
If variety of disturbances > the variety of responses, then the system becomes unstable (last case).

What defines the input and the output of a System?

a. goal of model

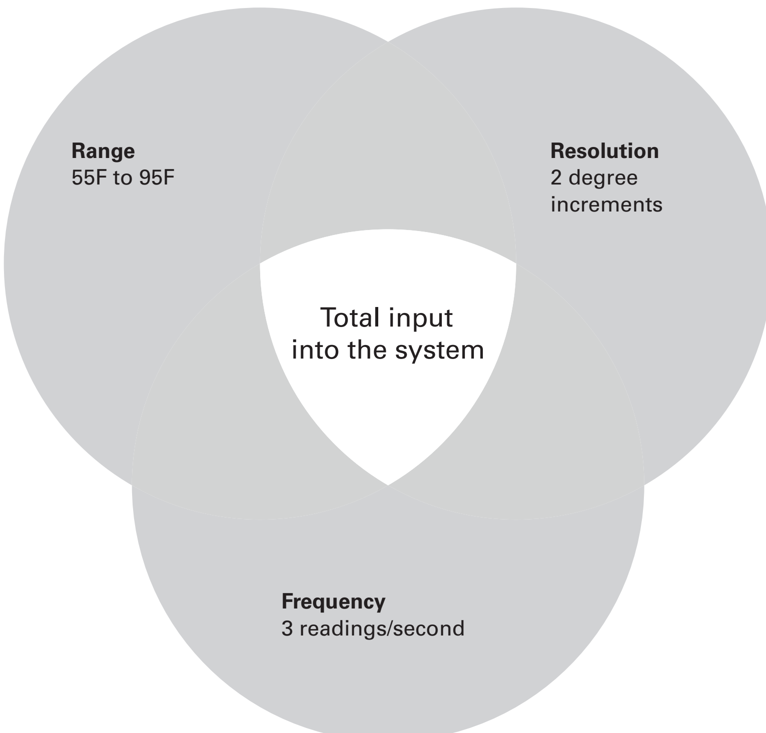
The figure presents the parameters of the sensor and actuator in a specific case. These parameters have direct bearing on the variety of the system. The use of the Venn diagram is metaphorical only.

b. description

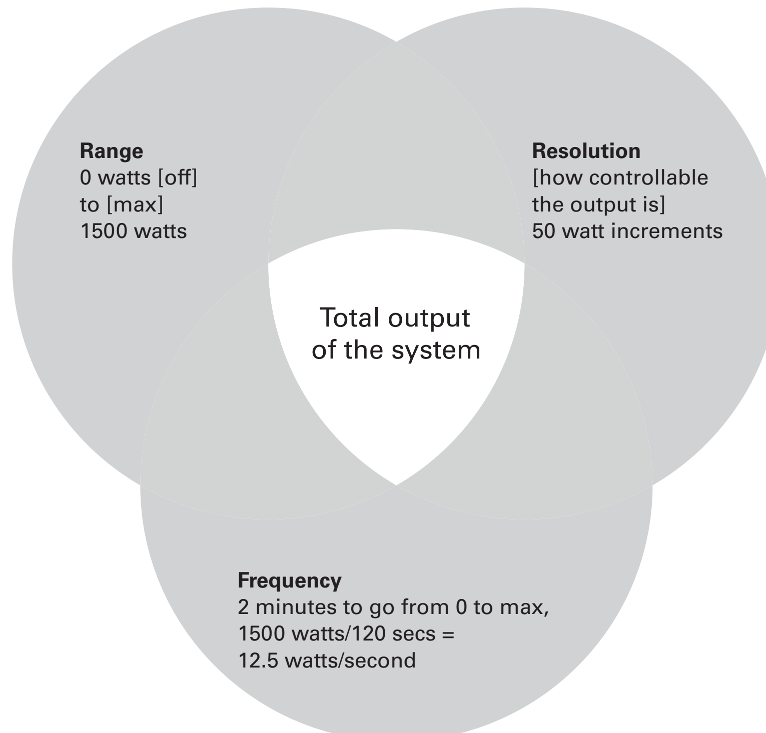
Range, Resolution, and Frequency (latency) are parameters for both the sensor and actuator of any system. For the specific case of a space heater, the breakdown of these parameters is shown.

What defines the input and the output of a System?
Example: Space Heater

Sensor



Actuator



Defining resolution, frequency, and range within an sensor

a. goal of model
The graph quantifies the parameters of the operation of the temperature sensor of a space heater.

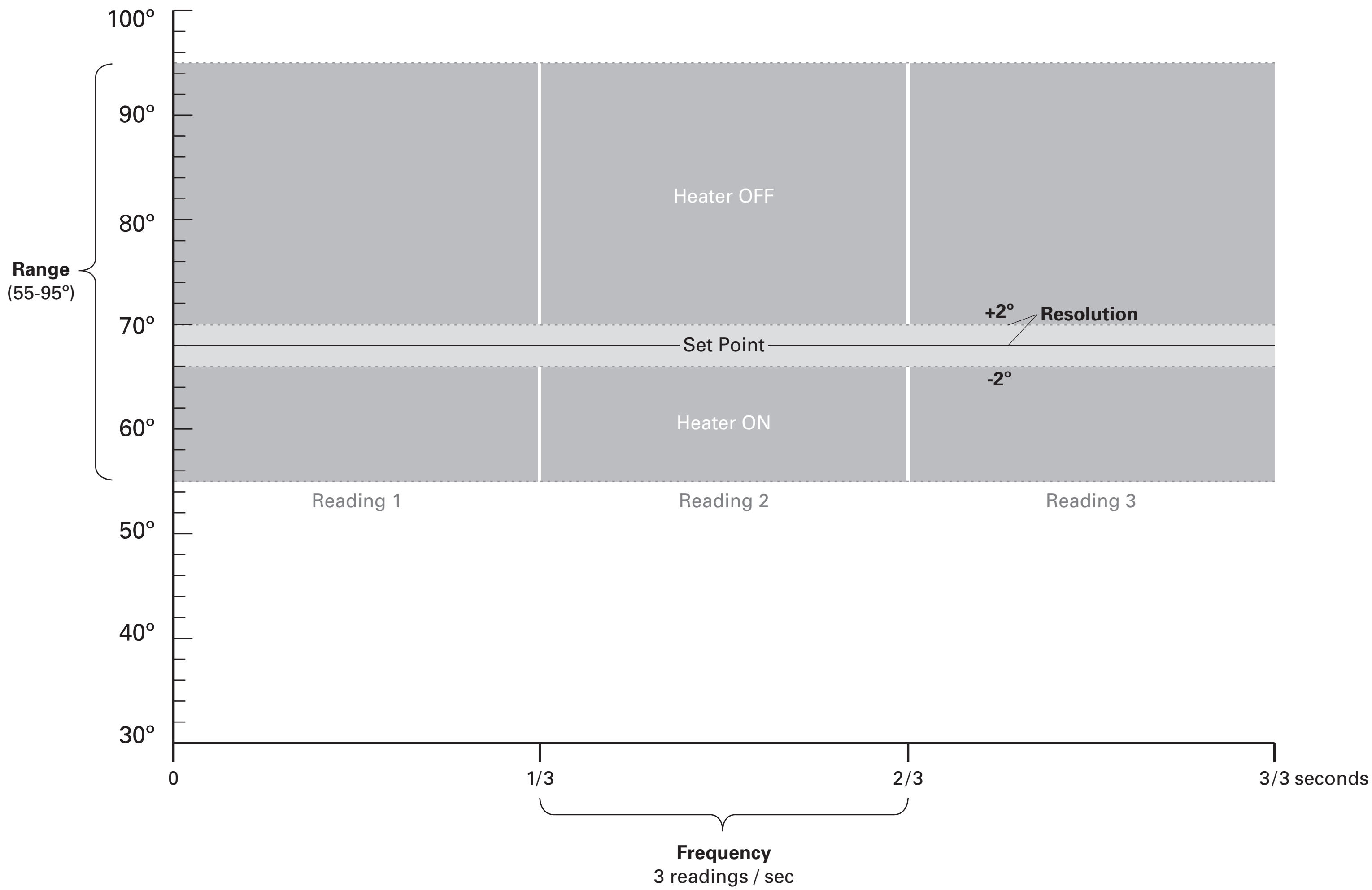
b. description
The temperatures at which the sensor changes its output, and how frequently the sensor takes a reading, are shown.

c. components and processes
The horizontal axis shows the frequency of (or latency between) readings by the sensor of the temperature, that of 3 times per second.

The vertical axis shows the range of readings in which the sensor maintains the value of its other parameters, namely, its resolution and frequency. This range is 55° to 95°.

The horizontal, lightly-shaded area of the graph shows the accuracy of its readings, which occur within 2° of a given value.

Defining resolution, frequency, and range within an sensor
Example: Space Heater



Defining resolution, frequency, and range within an actuator

a. goal of model
The graph quantifies the parameters of the actuator of a space heater.

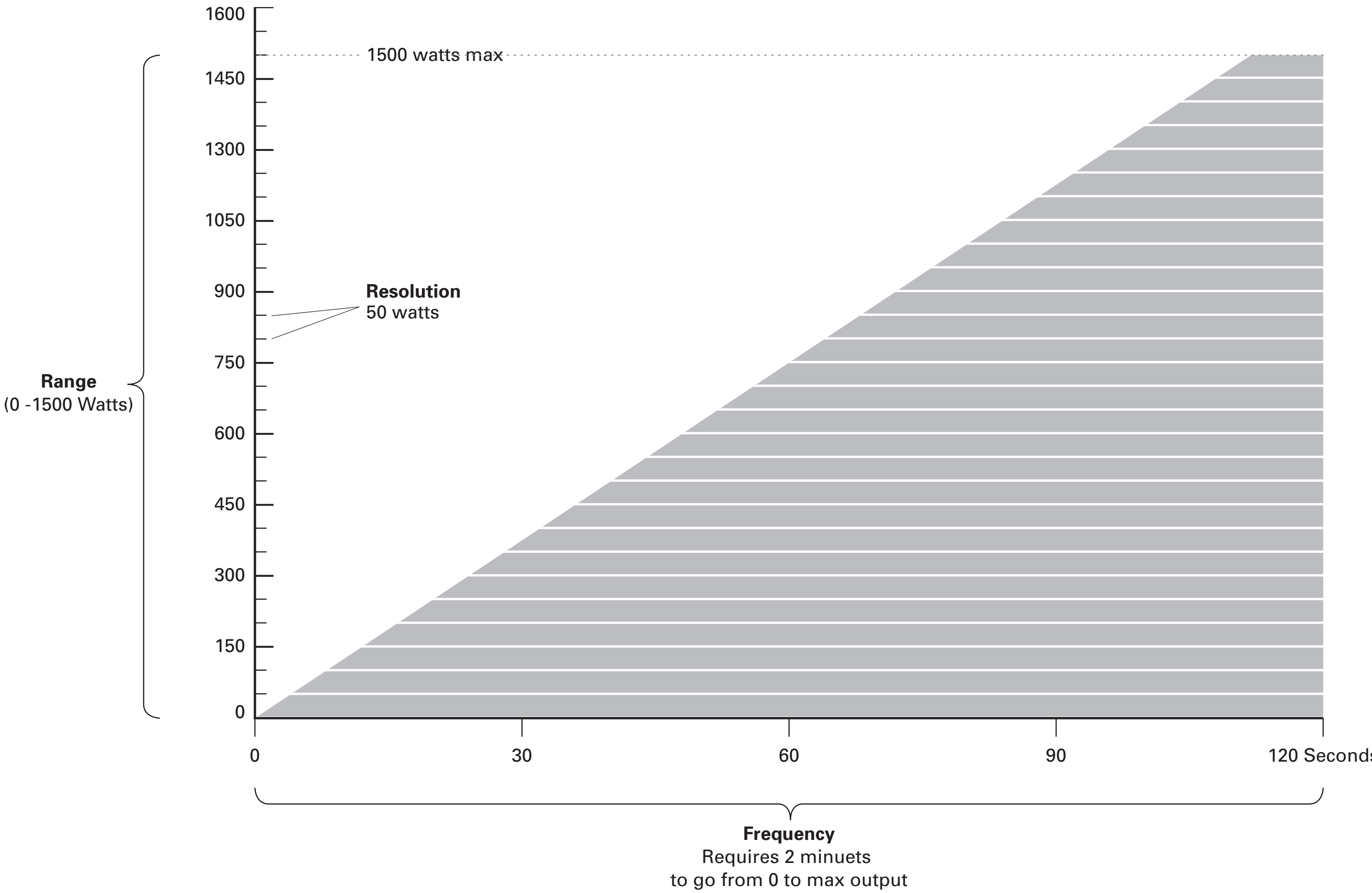
b. description
The heat output of the actuator, and the rate at which it produces heat, are shown.

c. components and processes
The horizontal axis shows the time in seconds that the heater takes to go from completely off to completely on (maximum heat output). The graphs shows this process to take 120 seconds. This parameter is called frequency (or latency) because it describes the time required for the heater to act.

The vertical axis shows the range of potential heat output for the space heater. The span of potential output is from 0 watts (off) to 1500 watts (completely on and warmed up). This is called the range of the actuator. Control of the heat output has a resolution of 50 watts, that is, the finest grain of control of the actuator is in roughly 50-watt increments.

The shaded area of the graph shows the relationship of time to heat output, assuming the heater is turned on full and the environmental disturbance is unchanged. The linear increase of output is an ideal case, while real-world heaters are likely to have non-linear heat-up times, but this is not material to most designs.

Defining resolution, frequency, and range within an actuator
Example: Space Heater



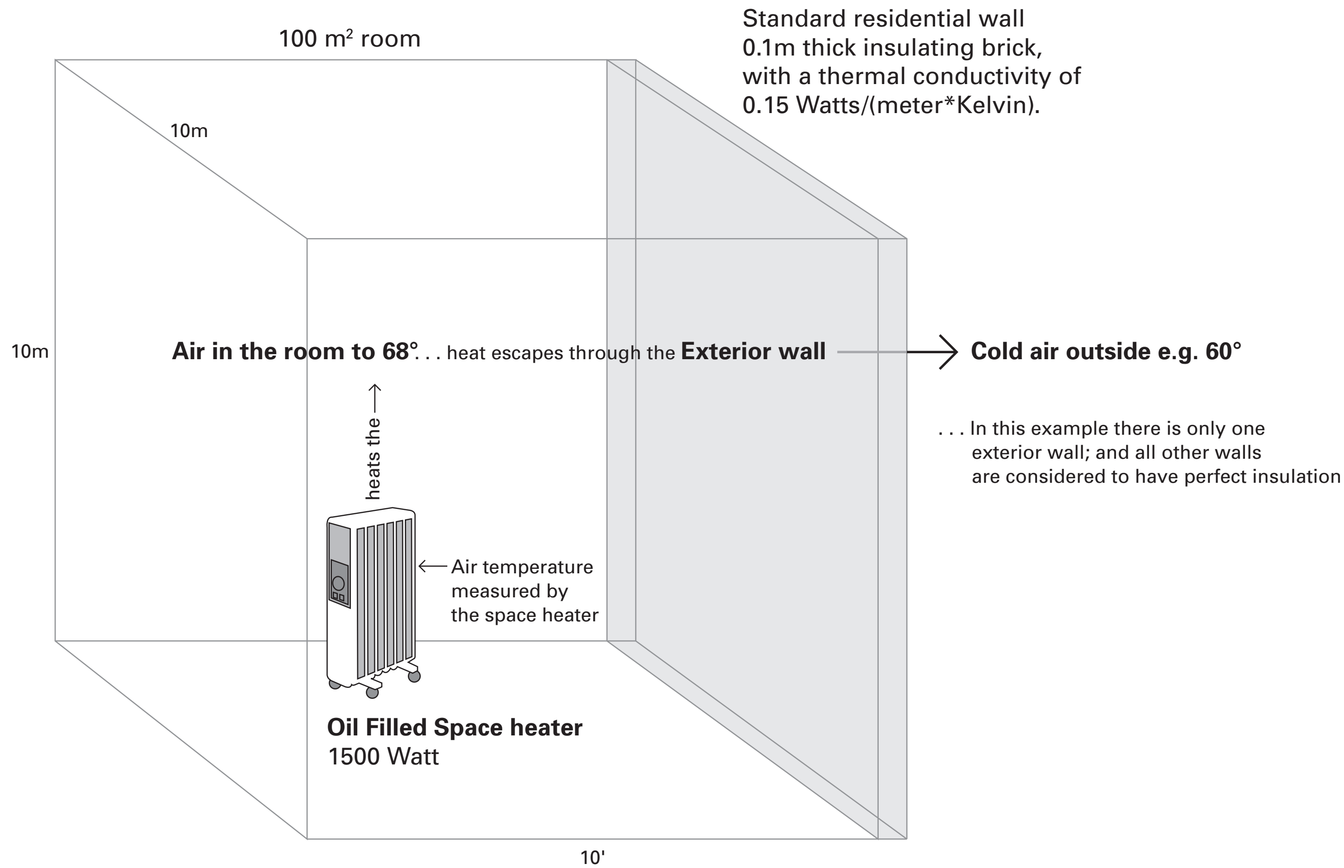
Determining the effective range of a space heater

a. goal of model
The model and graphs on subsequent pages provides a detailed and quantitative analysis of the variety of a room space heater.

b. description
Specifications of a space heater, the heat transmission qualities of a room, and outside conditions are used to define a specific case for computing the variety of a system.

Effectiveness of the heating system could be improved by adding insulation to the wall or increasing the heat output capacity of the heater.

Determining the effective range of a space heater
(How much variety does it have?)



Determining the Effective Range
The heater can maintain the room at 68° when the outside temperature is less than or equal to 68°, and greater than or equal to some minimum temperature T that we have to find. This T is characterized by the fact that it causes the rate of energy loss through the wall to be exactly equal to the maximum rate at which the heater can bring energy into the room.

An equation describing this is:
rate of energy transfer = k*(T_{in} - T_{out})*(wall area)/(wall thickness)

At what Temperature does the space heater fail?
Using the equation above we find that T_{out} **= 283.1K** or **50ºF**— when the outside temperature falls below 50ºF, the space heater will no longer be able to maintain the room at 68ºF.

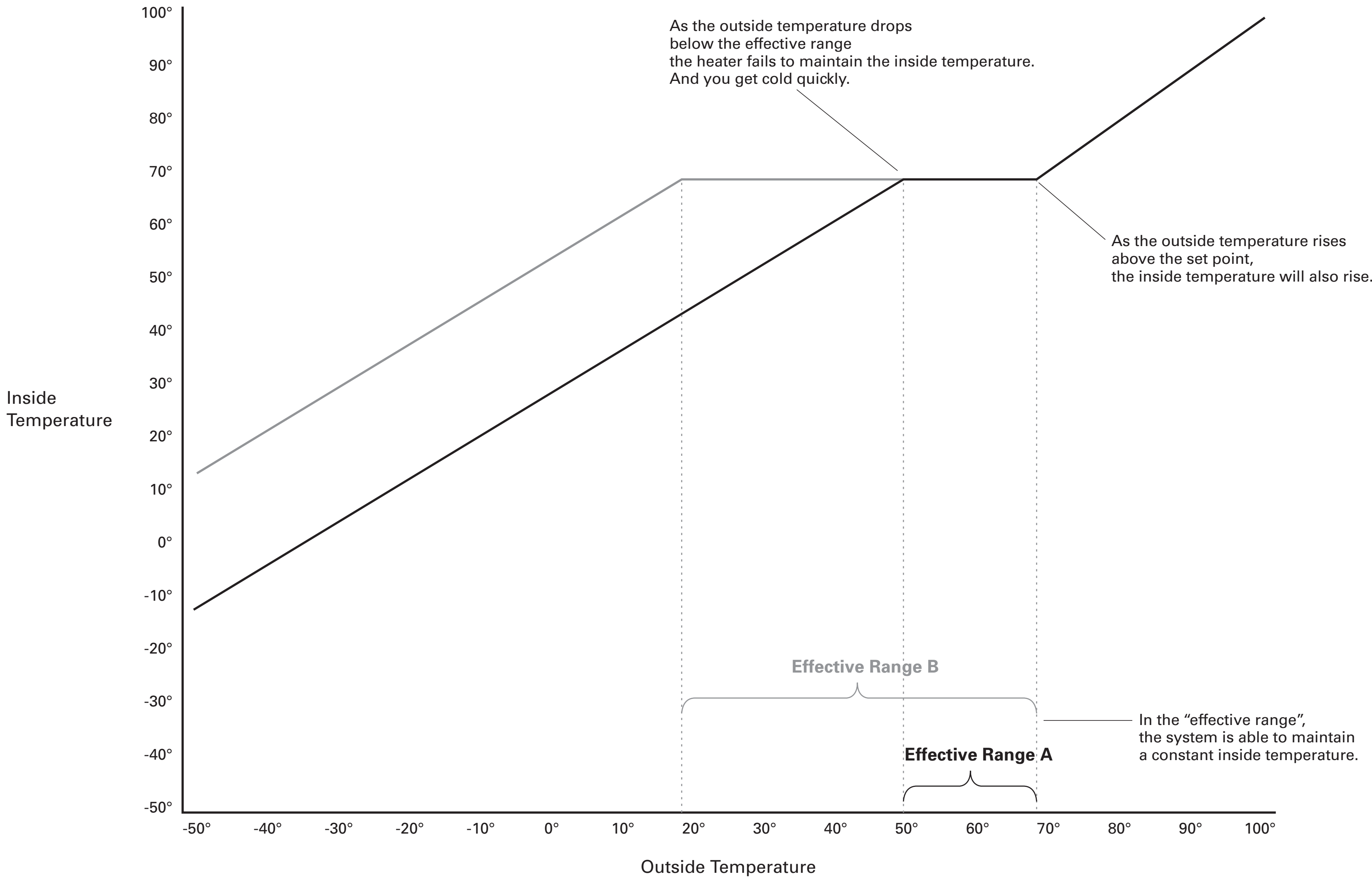
Elements within the Current Situation:
Space heater output = 1500 Watt (5120 BTU/hr)
Wall area = 100 m²
Wall thickness = 0.1 m
68ºF = 20ºC = 293.15ºK
Thermal conductivity for k (insulating brick) = 0.15 Watts/(meter*Kelvin).

Using the equation above , we find that T_{out} equals 283.15ºK (50ºF).
Keep in mind that this result is for a 10 centimeter thick wall of insulating brick.

Graphing the effective range of a space heater

a. goal of model
The graph shows the effective range—the conditions under which the system achieves requisite variety—for a specific system and environment.

Graphing the effective range of a space heater



These figures are only intended as a theoretical example.

In the previous example, the effective range of the space heater is relatively narrow, due to the amount of heat lost to the cold air outside. Above we can see the effective range from the previous example (**Effective Range A),** in comparison to a room of equal proportions, but with improved insulation (**Effective Range B)**.

Effective Range A
Insulating brick R-Value = 3.8 (0.15 Watts/meter*Kelvin).

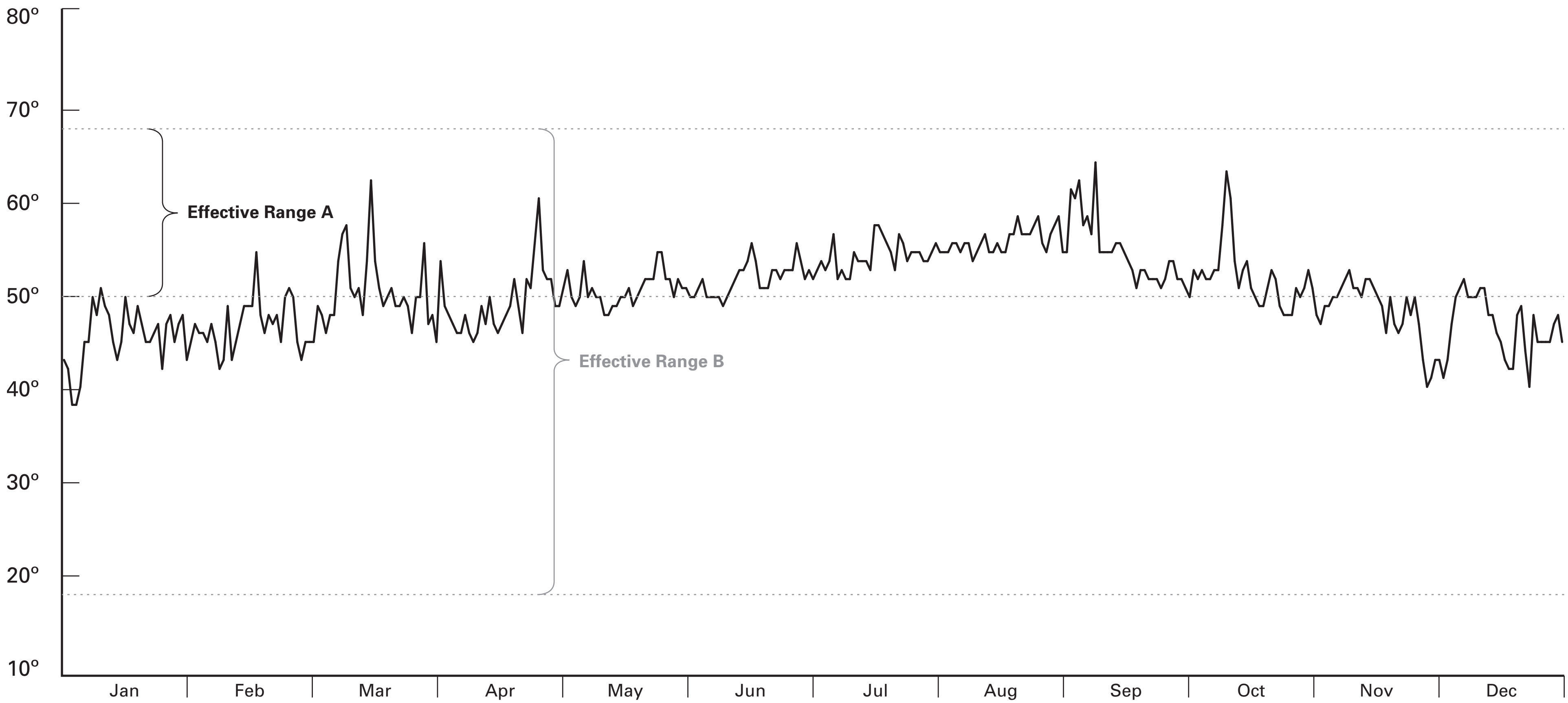
Effective Range B
2"× 4" construction & standard insulation R-Value = 10.5

Where does the space heater fail?

a. goal of model
The graph plots actual temperature for a city against the effective ranges of space heater described in previous pages.

b. description
By contrasting the two ranges, Effective Range A and Effective Range B, the graph highlights the implications of careful calculation of the variety of the system versus the variety of the environment. In this case, a system designed for Effective Range A would achieve its goal for mid-June through mid-October, only. The more expensive system designed for Effective Range B, however, achieves its goal for the entire year—at least, for the specific enivironmental conditions of the year shown.

Where does the space heater fail?



Daily Low Temperature
San Francisco, California 2004

Requisite Variety: Social Example
Los Angeles Lakers

a. goal of model
The diagram shows the application of the concept of variety to a social example, that of analyzing the capabilities of a basketball team in terms of the quality (variety) of its individual players.

b. description
The diagram shows the five starting players for each team with their salaries. Variety of an individual player is derived from his salary; the higher the pay, the "better" the player which, in the game of basketball, is interpreted to mean his capacity to respond in real-time to conditions of play; that is, the variety of the player versus the variety of the environment, that of the game itself.

c. components and processes
On the left side is shown a comparison of players of the losing team, the Los Angeles Lakers, and the winning team in the Semifinals of the 1995 West Conference. The sum of the salaries is shown at the bottom, implying that the variety of the Lakers fell short of that of their opponents in this game.

In contrast, when the Lakers played in the NBA championship 5 years later, the team was completely different and had the advantage over their opponents in salary and, therefore, in variety. This time they won.

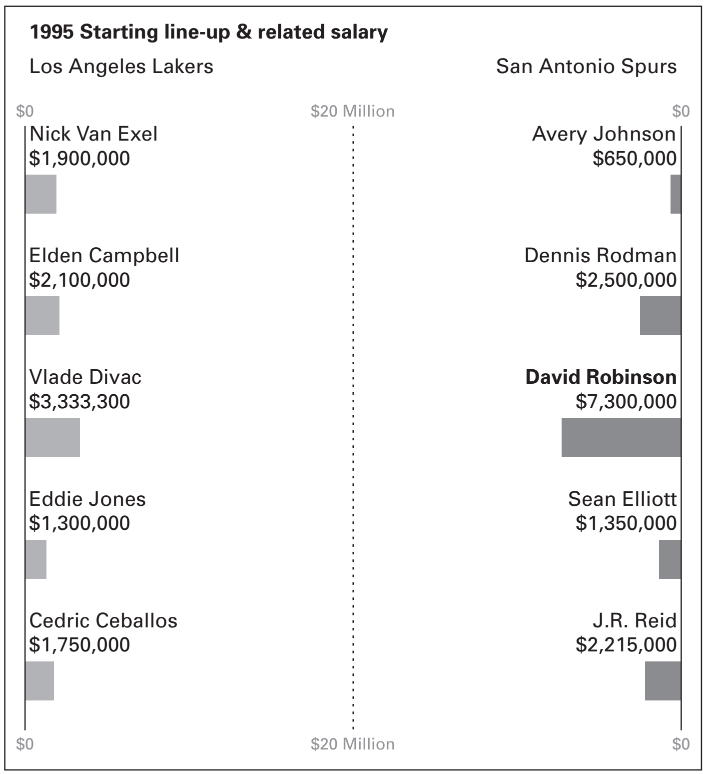
d. important aspects of model/breakthrough
While not strictly precise, the use of salary as proxy for variety, and the understanding that comes from the ensuing analysis, are valid examples of applying the concept of variety to systems that are social and involve human components.

Requisite Variety: Social Example—Los Angeles Lakers

Money is a proxy for player performance.
In this case increased Laker spending seems to have increased variety.

Lost West Conference Semis in 1995
to the San Antonio Spurs (4-2)
Finished 3rd in NBA Pacific Division (48-34)

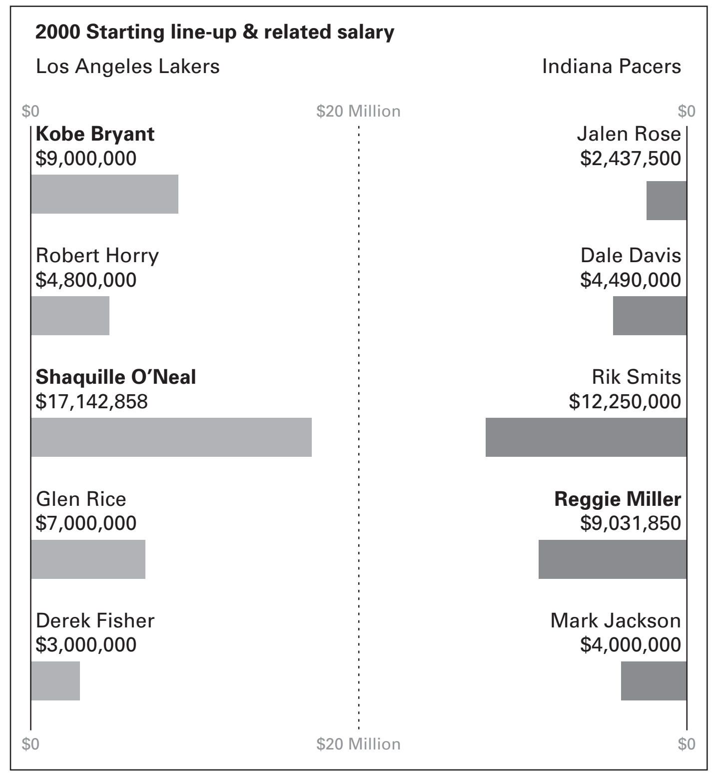
Los Angeles Lakers	**San Antonio Spurs**
Coached by: Del Harris	**Coached by: Bob Hill**
10 yrs. Coaching	5 yrs. Coaching
53% Wining average	53% Wining average



Starting Line-up Salary Totals
$10,383,300 (26% below the Spurs) $14,015,000

Won the NBA Championship in 2000
by defeating the Indiana Pacers (4-2)
First Championship in 12 yrs. (*also first year w/Phil Jackson*)
Finished 1st in NBA Pacific Division (67-15)

Los Angeles Lakers	**Indiana Pacers**
Coached by: Phil Jackson	**Coached by: Larry Bird**
10 yrs. Coaching	3 yrs. Coaching
75% Wining Average	69% Wining Average



Starting Line-up Salary Totals
$40,942,858 (23% above the Pacers)
$32,209,350