Interventionist Causation in Thermodynamics

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The interventionist account of causation has been largely dismissed as a serious candidate for application in physics. This dismissal is related to the problematic assumption that physical causation is entirely a matter of dynamical evolution. In this article, I offer a fresh look at the interventionist account of causation and its applicability to thermodynamics. I argue that the interventionist account of causation is the account of causation that most appropriately characterizes the theoretical structure and phenomenal behavior of thermodynamics.

1. Introduction. The interventionist account of causation has been largely dismissed as a serious candidate for application in physics. For example, a dismissal of this sort is evident in the words of theoretical physicist Peter Havas: "We are all familiar with the everyday usage of the words 'cause' and 'effect'; it frequently implies the interference by an outside agent (whether human or not), the 'cause', with a system, which then experiences the 'effect' of this interference. When we talk of the principle of causality in physics, however, we usually do not think of specific cause-effect relations or of deliberate intervention in a system, but in terms of theories which allow (at least in principle) the calculation of the future state of the system under consideration from data specified at a time t_0" (1974, 24). And worries about the relevance of the interventionist account of causation in physics come not only from physicists but also from philosophers—even those who favor interventionism: "There are important differences between, on the one hand, the [interventionist] way in which causal notions figure in common sense and the special sciences and the empirical assumptions that underlie their

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application and, on the other hand, the ways in which these notions figure in physics" (Woodward 2007, 67).

The reasons for dismissals and worries like those above are related to a common (but problematic) assumption that causation in physics has something to do with the dynamical evolution of a closed system. The problem is that, in our preoccupation with dynamical evolution and closed systems, we tend to forget or neglect those areas of physics for which we do not have complete equations of motion or for which it does not make sense to consider entirely closed systems. And it is in those areas that the dynamical view of physical causation makes less sense and interventionism finds its home.

In this article, I propose to take a fresh look at the interventionist account of causation and its applicability to one of those neglected areas of physics: thermodynamics. I will argue that an interventionist analysis of thermodynamics succeeds where the dynamical view of physical causation fails. As I will show, all theorizing in thermodynamics requires careful definition of the "system" under consideration, which necessarily involves attending to the boundaries that enclose the system and the conditions imposed on those boundaries. Once boundaries are adequately specified, we end up with a strong distinction between the internal properties and processes of the system and those external influences that constrain the internal dynamics. It is in the distinction between internal properties and external influences that the natural fit between the structure of thermodynamic theorizing and the interventionist account of causation becomes apparent.

The plan of this article is as follows. In section 2, I show that interventionist reasoning is inseparable from the structural foundation of thermodynamic theory. In section 3, I show how "driving forces" and their conjugate fluxes provide a rich basis for meaningful interventionist causal claims in thermodynamics. In section 4, I use the success of interventionist causal analysis in thermodynamics to make some broader concluding remarks.

2. The Centrality of Manipulated Equilibrium. Thermodynamic theorizing is structured around the characterization of equilibrium states and the processes by which systems move from one equilibrium state to another. But just what is a thermodynamic equilibrium state?

A thermodynamic equilibrium state is the state of a system that is not undergoing a change (thermal, mechanical, or chemical). However, an equilibrium state is not a spontaneous occurrence. Natural thermodynamic systems are in constant flux. They engage in all sorts of interactions: they transfer heat, push and pull on one another, change their volume, and chemically react. The very idea of a thermodynamic "system," which can only be defined by the location or nature of its boundaries, is in itself a theoretical concept that we impose on the world in order to do thermodynamic "bookkeeping" (Dill and Bromberg 2011, 93). In order for a thermodynamic system to

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achieve an equilibrium state, the system must have been allowed to relax for a sufficient amount of time without the disturbing external influences of uncontrolled contact with other systems. And such a condition requires boundaries that isolate it—or otherwise control exchanges—from other systems. Often those boundaries are put in place artificially, by human intervention.

Consider, for example, the air in an ordinary room. If we define our thermodynamic system in relation to the walls and doors of the room, we can say that the system has a fixed volume. If no massive weather change is currently occurring, we can assume that the air pressure in the room is approximately constant (not by isolation but by contact with an external system whose pressure is approximately constant). If some kind of air conditioning system is in place and has been running for some time, we can also say that the temperature of the room is approximately constant. We can say that most of the chemical reactions occurring in the room are in a steady state and that the concentrations of various gases are relatively uniform (except perhaps for some minor concentration gradients near any plants or people located in the room), with equal flow into and out of the room for each type of gas. Notice, now, that even this almost-equilibrium state requires artificial maintenance (the rigidity of walls, contact with an exterior reservoir supplying constant pressure, the continuous work of the air conditioner, etc.). Stricter equilibrium states require much more careful isolation and maintenance, and true equilibrium states (which only exist in theory) require idealized boundaries (e.g., perfect thermal insulators, frictionless pistons, perfectly rigid containers).

There is something of a tension, however, in the way that we think about equilibrium states. On the one hand, equilibrium states are the product of external conditions imposed on a system. On the other hand, once we consider those external conditions as given, a system will naturally or spontaneously tend toward the equilibrium state allowed by the constraints. But that spontaneous or natural behavior cannot be conceived of without external constraints being placed on the system in question. To even conceive of an equilibrium state, we must ask about the conditions imposed on its boundaries. What kind of walls enclose it? Permeable, semipermeable, impermeable? Rigid or flexible? Adiabatic or conducting? There is no such thing as an equilibrium state unless the boundaries of the system are well defined.[1] And the conditions imposed on those boundaries constitute external interventions on the system; they effectively set various thermodynamic variables to take on certain values. For example, conducting walls that put a system in contact with a thermal reservoir are effectively a way of intervening on temperature.

1. In fact, a system with no defined boundaries or external constraints is effectively a universe, and its fate is something like the "heat death" discussed by Helmholtz (1856) and Thomson (1862/1889).

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Likewise, a semipermeable boundary is a way of selectively intervening on particle concentrations in the system. (I return to the question of how to conceive of boundary conditions as interventions on thermodynamic variables below in sec. 3.)

Thus, thermodynamic equilibrium states are inherently manipulated states—manipulated to be so either by human design or by some other mechanism that effectively imposes equilibrium conditions by external intervention. And these external manipulations or interventions, which impose values on certain thermodynamic variables, are entirely consistent with the concept of an intervention that has been developed by Woodward (2003) and others. According to the interventionist account of causation, an intervention directly forces a variable to take on (or remain fixed at) a certain value. Furthermore, Woodward's definition of an intervention makes no reference to human action, and thus any entity or structure playing the role of setting certain variable values or holding them fixed can fulfill the requirements for intervention. For example, a cell membrane is a structure that effectively intervenes to maintain a certain equilibrium internal to the cell, by keeping interior and exterior pressures equal and by maintaining certain chemical concentrations by only allowing for select passage into and out of the cell.

Now how do these manipulated equilibrium states figure into theorizing about thermodynamic processes? We begin by representing our system of interest by reference to a *thermodynamic configuration space*. The thermodynamic configuration space is the set of all possible equilibrium states of a system, where the coordinates of that space are a relatively small number of macroscopic thermodynamic variables and each point in the configuration space represents a distinct equilibrium state. For example, we might choose as coordinates the following parameters: internal energy (U), volume (V), and the particle numbers of the various species present ($N_1, N_2, \ldots, N_i$). Then the entropy function for our system, $S = S(U, V, N_1, \ldots, N_i)$, will define a hypersurface within the configuration space (see fig. 1).

With this thermodynamic configuration space and the hypersurface defined by the entropy function in place, we can begin to theorize about any ordered sequence of states (call these A, B, C, . . .) located on the hypersurface. Notice that a curve drawn through this sequence of states looks something like a process (in fact, we call it a *quasi-static process*) in that it represents a series of changes undergone by the system. However, such a curve can be nothing like a real process, because real processes involve nonequilibrium states and the curve represents a system that remains in equilibrium along its entire length. Furthermore, the curve could never represent the autonomous trajectory of a system, since every state that makes up the path is an equilibrium state and no isolated system would move from one equilibrium state to another spontaneously. So in order to think about a quasi-static process as something like a process, we must think of a system being "led"—

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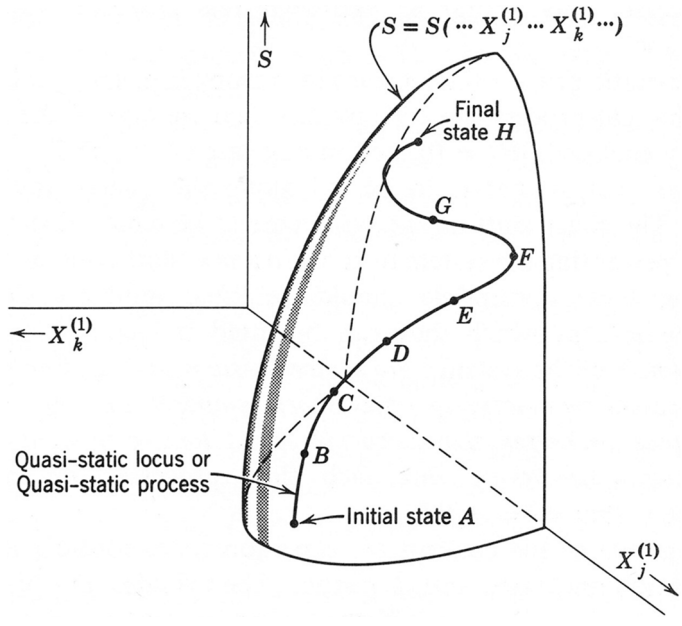


Figure 1. Representation of a quasi-static process in thermodynamic configuration space. From Callen (1985).

by a series of external interventions—through the succession of desired states via "hops." We effectively imagine the system being "corralled" through the sequence of equilibrium states. And by imagining the sequence of hops between states to be very small and carried out by very tiny interventions, we can approximate a smooth curve more and more closely (in fact, arbitrarily closely).[2]

In summary, the structural foundation of thermodynamic theory is the set of equilibrium states and the quasi-static "processes" that can be drawn like lines through the space of such states. As I have argued here, the very idea of an equilibrium state is not possible without reference to boundaries and the constraints that set the value of certain thermodynamic variables within those boundaries. Furthermore, we cannot think about quasi-static "processes," which are sequences of those equilibrium states, without thinking about a series of infinitesimal external interventions that force a system from one equilibrium state to the next. It is in this sense that interventionist reasoning is inseparable from the structural foundation of thermodynamic theory.

In the next section, I discuss thermodynamic theorizing in greater specificity. As I will show, the interventionist view of causation maps naturally

2. My discussion here closely follows that of Callen (1985, chap. 4).

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onto the use of potential functions when theorizing about a system undergoing a process.

3. Thermodynamic Potentials and Driving Forces. The equilibrium state toward which a system will tend, given the conditions imposed on its boundaries, is governed by the energy and entropy considerations provided in the First and Second Laws of thermodynamics. The First Law tells us that any change in the internal energy (U) of a system will be equal to the total amount of energy it gains through energy exchange with the external world, in the form of heat or in the form of work. The Second Law tells us that any isolated system (i.e., any closed system with fixed internal energy) will tend toward its state of maximum entropy (S). The Second Law also has the result that the internal energy of any closed system with fixed entropy will be minimized. However, neither internal energy nor entropy are directly measurable, nor do we have a specific function that tells us their dependence on other state variables. What we do have, however, are other equations of state (e.g., the ideal gas law) in addition to equations for U and S in differential form, which tell us about the way in which small changes in other state variables relate to small changes in energy and entropy:

$$dU = TdS - pdV + \sum_j \mu_j dN_j, \tag{1}$$

$$dS = \left(\frac{1}{T}\right) dU + \left(\frac{p}{T}\right) dV - \sum_j \left(\frac{\mu_j}{T}\right) dN_j, \tag{2}$$

where T is absolute temperature, p is pressure, V is volume, μ_j is the chemical potential for species j, and N_j is the number of particles for species j. The above equations (and other variant forms) are commonly referred to as *thermodynamic potential functions*.

Notice that each term in both equations above involves a pair of conjugate variables. The second term in equation (1), for example, involves pressure and volume as a conjugate pair. For every pair of conjugate variables, one of the variables is extensive (i.e., additive such that the property of a system is equal to the sum of that property for all of its component subsystems), while the other is intensive (i.e., independent of the size of the system). Looking again at the second term in equation (1) as an example, pressure is the intensive variable and volume is the extensive variable.

Depending on the factors controlled in a given experimental context, each pair of conjugate variables tells us something about a tendency of the system as it moves toward equilibrium in that context. Since conjugate variables will be extremely important for our purposes here, let us concentrate on one pair and use an example to decipher its practical meaning.

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Consider the term $(1/T)\,dU$ in equation (2) and the process pictured in figure 2. We begin with two systems A and B, each enclosed in a rigid container. System A begins at temperature T_A and system B at T_B, where $T_A \neq T_B$. The two systems are then brought into thermal contact with one another but remain thermally insulated from the rest of the world. Now each system has an unknown entropy that can be expressed as a function of its internal energy, volume, and particle numbers, and since entropy is an extensive quantity, the total entropy of the combined system can be expressed as $S_{\text{Total}} = S_A(U_A, V_A, \mathbf{N}_A) + S_B(U_B, V_B, \mathbf{N}_B)$. Since entropy will be maximized at equilibrium, we use equation (2) to write the differential expression for S_{Total} and set it to zero:

$$dS_{\text{Total}} = \left(\frac{1}{T_A}\right) dU_A + \left(\frac{p_A}{T_A}\right) dV_A - \sum_i \left(\frac{\mu_{A_i}}{T_A}\right) dN_{A_i} + \left(\frac{1}{T_B}\right) dU_B + \left(\frac{p_B}{T_B}\right) dV_B - \sum_j \left(\frac{\mu_{B_j}}{T_B}\right) dN_{B_j} = 0. \tag{3}$$

If we assume that there is no particle exchange between the two systems and that no chemical change occurs within each system, we can eliminate the terms that allow for changing particle numbers. And since the containers are rigid, we can eliminate the terms that allow for changing volume. Furthermore, given that the combined system is isolated from the external world, the total internal energy of the combined system must remain constant, and any change in energy of either system must be compensated by a change in energy of the other. Thus, $dU_A = -dU_B$. So we have the following simplified expression:

$$dS_{\text{Total}} = \left(\frac{1}{T_A} - \frac{1}{T_B}\right) dU_A, \tag{4}$$

which will be equal to zero (i.e., attain equilibrium) when $T_A = T_B$.

Thus, we have derived the well-known result that two objects brought into thermal contact will reach equilibrium when their temperatures are equal.

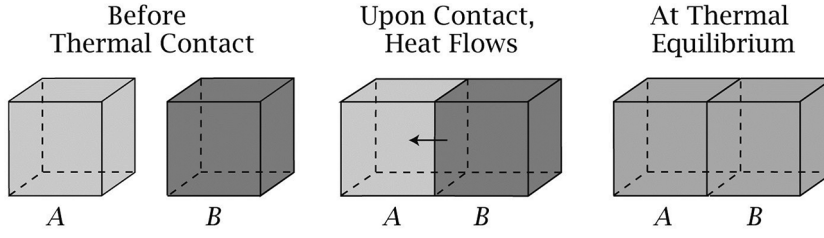


Figure 2. Two thermodynamic systems A and B before, during, and after arriving at thermal equilibrium. From Dill and Bromberg (2011), 100.

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But more important for our purposes here, we can interpret the factors in equation (4) in light of this equilibration process. The difference in temperatures between the two systems leads to a nonzero value of the factor $(1/T_A) - (1/T_B)$, which effectively acts as a "force" driving a change dU_A in the internal energy of system A. More generally speaking, when a system is placed in thermal contact with a system at a different temperature, the temperature difference between the two systems acts as a force driving an exchange of heat energy between the systems. Phrased in terms of a system and its surroundings, $1/T$ describes the tendency of a system to exchange heat with its environment; it is the incremental relaxation that a system experiences in transferring a small bit of its energy dU.[3]

Physicists commonly use the language of "driving forces" in referring to the intensive parameters in the thermodynamic potential functions. Looking back again at equation (2), a difference between the pressure p of the system and its environment will act as a driving force for an exchange of volume dV between the system and its environment, and a difference between the concentration of a particular species μ_j in the system and its environment will act as a driving force for exchanges of particles of the respective species with the environment (dN_j). The force or tendency represented in each of the conjugate pairs (T, p, $\boldsymbol{\mu}$) can act, separately or together (depending on the constraints imposed on the process), to drive changes in its paired extensive variable (dU, dV, or $d\mathbf{N}$, respectively) and thus to drive the system and its environment toward the equilibrium state of maximum entropy.[4]

This "driving force" language—and its basis in the way in which the environment exchanges energy and entropy with a system—matches the way in which relationships among thermodynamic variables would be modeled by the interventionist account of causation. According to the interventionist account, a variable X is an interventionist cause of another variable Y if there is a possible intervention on X that will change the value of Y (or the probability distribution over the values of Y) when the values of all other variables in the system remain fixed.[5] In physical experiments, the condition that

3. Alternatively, we could have begun with the thermodynamic potential function for internal energy (eq. [1]) to derive the same result.

4. Physicists use the language of "driving forces" in both the entropy and energy representations. When we flip between the energy picture of a system and the entropy picture of that same system, the metric by which we measure progress toward equilibrium changes. Each metric has its own way of characterizing the driving force because, in changing our metric of progress, there is a transformation on the force term. Still, physically, it is one and the same force driving the system toward equilibrium. This representational change in the physical equations mirrors a widely noted feature of the interventionist account of causation: when we change the set of variables with which we characterize a causal system, our characterization of the causal relationship itself can change.

5. I have ignored some technical details for the sake of simplicity here. See Woodward (2003, 59) for the more precise interventionist criteria for X's being a type-level direct cause of Y and X's being a type-level contributing cause of Y.

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the values of all other variables in the system remain fixed across changes in the intervention on X is often enforced using what I will call "auxiliary interventions" on those variables. To see how interventionist treatment matches the "driving force" language, let us consider the temperature equilibration case above, with system A as the causal system under investigation.

Consider the set of thermodynamic variables characterizing system A when we consider the temperature equilibration process in terms of maximization of entropy: volume V_A, the set of particle numbers for each species $\mathbf{N}_A$, temperature T_A, and internal energy U_A. Each of these variables is represented in figure 3. The primary intervention in the temperature equilibration case was the operation of placing system B in thermal contact with system A. This intervention occurred specifically under conditions in which the volume V_A and particle numbers $\mathbf{N}_A$ of system A were held constant; the enforcement of constant values of V_A and $\mathbf{N}_A$, by enclosing the system within rigid impermeable walls, constitutes the set of auxiliary interventions in this case. Under the conditions set by these auxiliary interventions, the primary intervention produced a change in T_A, since the original temperatures of the two systems were not equal, and this change in temperature resulted in a change in the internal energy (U_A) of the system. And since, under conditions where all other variables are held constant, the intervention was an intervention on T_A and resulted in a change in U_A, we can say that T_A is an interventionist cause of U_A.

To further flesh out the causal claim being represented by the arrow from T_A to U_A in figure 3, we can contrast varying interventions in which we put

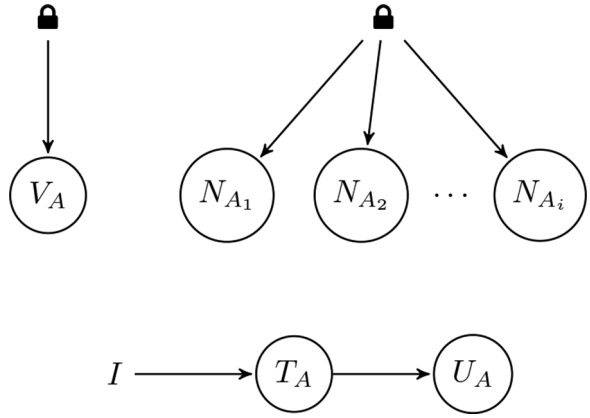


Figure 3. Interventionist causal graph of the temperature equilibration process in which system A, originally at temperature T_A, is brought into contact with another system B, originally at temperature T_B. The variable I represents the intervention that places the two systems in contact and thus changes the value of T_A. The lock symbols represent the auxiliary interventions that hold V_A and $\mathbf{N}_A$ fixed.

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system A in contact with system B at varying temperatures T_{B1}, T_{B2}, . . . T_{Bn}, while still holding V_A and $\mathbf{N}_A$ constant at the same values. Under such varying interventions, we will find that there are corresponding variations in the final T_A and U_A. Therefore, the interventionist account confirms that the temperature T_A of system A is a cause of its internal energy U_A. In general, interventions on temperature lead to changes in internal energy via exchange of heat when volume and particle numbers are held constant. Such a causal claim seems to be precisely what physicists mean to convey when they use "driving force" language with respect to temperature.

The intervention in the above case, where we have an equilibration process between two finite systems with differing initial temperatures, is an example of a "soft" or "parametric" intervention in that it modifies the temperature of our system rather than determining it completely.[6] When we put system A with its initial temperature T_A in contact with system B with its initial temperature T_B, the combined system finds an equilibrium temperature somewhere between the initial values of T_A and T_B. But thermodynamics also provides conceptual tools for theorizing about "hard" or "structural" interventions that entirely determine the value of an intensive parameter for a system. We call these theoretical entities "reservoirs" or "baths," and they have the property of being able to exchange one or more extensive quantities while their corresponding intensive properties remain constant. For example, an energy bath (i.e., a temperature reservoir), by virtue of its size, is able to exchange energy with a system with which it is put in contact with negligible effect on its temperature. Likewise, a volume bath (i.e., a pressure reservoir) is able to exchange volume while remaining at constant pressure, and a particle bath (i.e., concentration reservoir) is able to exchange particles while maintaining constant particle concentrations. When we theorize about cases in which we put a system in contact with a reservoir instead of a finite system, we consider a hard intervention that determines the value of the relevant intensive variable in our system. Such theoretical experiments bring the interventionist causal structure into even clearer relief: putting a system in contact with a reservoir is an intervention that sets the value of an intensive variable in the system, which in turn results in a change in the corresponding extensive variable.

Let us look at an example. Consider a system that is in an initial equilibrium state (p_0, T, $\mathbf{N}_A$). Suppose that we intervene on the system by bringing it into contact with a reservoir that maintains the same temperature T as the system but a different pressure p_{Res}. We might do so by releasing an initially locked piston, allowing it to move freely between the system and the reservoir (see fig. 4). The process that ensues will be ruled by a maximization of

6. For the distinction between soft and hard interventions, see Eberhardt and Scheines (2007).

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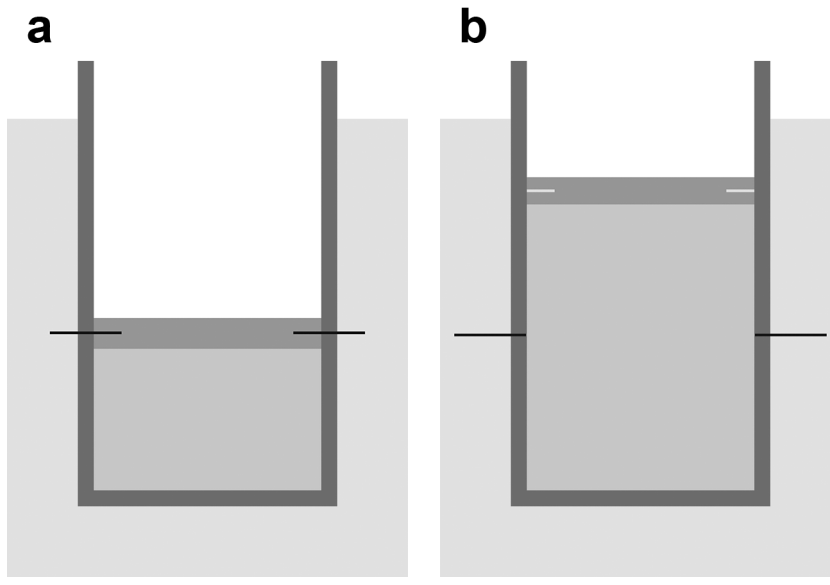


Figure 4. Pressure-driven process depicting (*a*) the system in its initial equilibrium state before the piston-locking pins are released and (*b*) the system once it has reached its new equilibrium state after the pins are released. Result of the case in which $p_0 > p_{\text{Res}}$ and the piston rises is shown, but all of the same considerations would apply in the case that $p_0 < p_{\text{Res}}$ and the piston falls.

the entropy of the total combined system, so we are interested in the condition where $dS_{\text{Total}} = 0$:

$$dS_{\text{Total}} = \frac{1}{T_{\text{Res}}}\, dU_{\text{Sys}} + \frac{p_{\text{Sys}}}{T_{\text{Res}}}\, dV_{\text{Sys}} + \frac{1}{T_{\text{Res}}}\, dU_{\text{Res}} + \frac{p_{\text{Res}}}{T_{\text{Res}}}\, dV_{\text{Res}} = 0. \quad (5)$$

Because of conservation of volume and conservation of energy, $dU_{\text{Sys}} = -dU_{\text{Res}}$ and $dV_{\text{Sys}} = -dV_{\text{Res}}$, so the above condition reduces to the following equation:

$$dS_{\text{Total}} = \left(\frac{p_{\text{Sys}} - p_{\text{Res}}}{T_{\text{Res}}}\right) dV_{\text{Sys}} = 0. \quad (6)$$

We can see here that it is the pressure difference between system and reservoir that is driving the exchange of volume. And again, this physical interpretation in terms of driving forces matches the interventionist causal account. By placing the system in contact with the reservoir, we set the pressure of the system to a new value, and the forced change in pressure results in a change in volume. Were we to impose a different pressure on the system

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by placing it in contact with a reservoir at a different pressure, we would see the corresponding volume change as well. Thus, pressure is an interventionist cause of volume (see fig. 5).

As shown in the examples above, the most important key to successful thermodynamic theorizing is the careful definition of the boundaries between systems and accounting for the transactions that occur at those boundaries. Interventionist reasoning fits naturally into thermodynamic theorizing because its distinction between the interventions external to a causal system and the causal relations internal to that system is perfectly applicable where thermodynamic boundaries are well defined. Since interventions are always performed on a causal system from outside, it is entirely natural to label exchanges between a system and its environment as interventions of the environment on those systems.

4. Conclusion. In this article, I have shown that there is a natural fit between thermodynamic theorizing and the interventionist account of causation. I therefore argue that the interventionist account is the most suitable account of causation for describing thermodynamic theorizing and our actual interactions with thermodynamic systems.

I suggested at the beginning of this article that we tend to assume that physical causation will have a dynamical form and that my identification of interventionism as the most appropriate account of causation in thermodynamics would run contrary to this assumption. It might be objected that this is a somewhat dull result, however. Thermodynamics, so the objection might

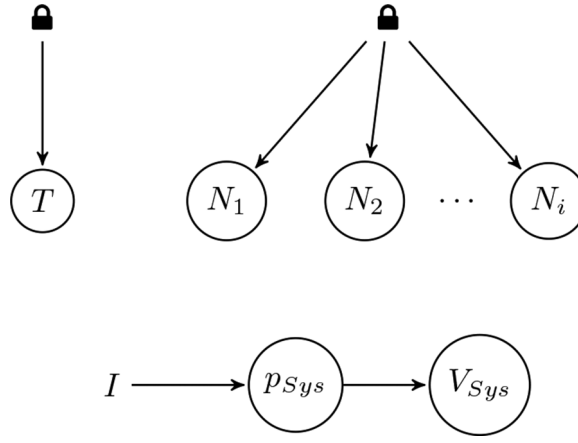


Figure 5. Interventionist causal representation of the pressure equilibration process depicted in figure 4. The variable I represents the intervention that places the system in contact with the pressure reservoir and thus changes the value of p_{Sys}. The lock symbols represent the auxiliary interventions that hold T and **N** fixed.

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run, is not "fundamental" physics, and so it is unsurprising that we should find interventionist causation rather than dynamic causation in a realm of physics that is . . . well . . . not dynamical. But such an objection would miss the point. Our common assumption that "physical causation" must refer to the dynamical propagations of systems is the result of our preoccupation with "fundamental" physics (which we also assume, almost by definition, must have a dynamical form) and neglect of those areas of physics that are considered to be "nonfundamental."[7]

So what is it to be a cause in (at least some of) physics? Here is a simple answer: an account of causation that appropriately characterizes the theoretical structure and phenomenal behavior of a domain of physics gives an account of what it is to be a cause in that domain of physics. And I have shown that the interventionist account does just that in thermodynamics.

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7. Increasingly, the study of "nonfundamental" theories has revealed that their relationship with "fundamental" theories is less straightforward than might be expected. For recent discussions in this vein, see, e.g., Batterman (2013). Furthermore, it is entirely unclear what the criteria for "fundamental" status are or whether undisputed criteria even exist. And with the criteria for fundamentality in doubt, it is hard to see what basis we might have for even expecting "fundamental" theory to always have dynamical form.

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