Instructor's guide **Goals**

- The number of pieces of information you need to specify a state/the number of independent variables is equal to the number of ways you can get energy into or out of the system (2 in the simplest thermo examples)
- Which variables are independent can be chosen for convenience.
- You cannot hold two variables constant and change the state if there are only two degrees of freedom.

Time Estimate: 30 minutes
Tools/Equipment

- Graph with empty T and p axes
- Graph of S and V contours on T and p axes
- (optional, for demonstration) $U(T, p)$ plastic surface (blue)

Intro

- Little is needed. Some students might be bothered by thinking about entropy if it hasn't been mentioned at all in class.
- This activity is a good follow-up to the "Changes in Internal Energy" activity about the 1st law of thermodynamics.

Whole Class Discussion:

- Get students to articulate that they needed 2 pieces of information to identify a state, but it didn't need to be the numbers located on the perpendicular axes - it could have been any two pieces of information.
- Introduce the language that simple thermal systems have 2 degrees of freedom (number of independent variables). The number of degrees of freedom is equal to the number of ways of getting energy into or out of the system. For simple thermal systems, you get energy into or out of the system through heat or work (1st law of thermodynamics)
- Changes in state also require specifying two changes - you can only hold 1 variable constant and change the state! If you hold two variables constant, you're stuck!
- There is freedom to choose which variables you want to be independent. "Choices" are usually related to what is controlled in an experiment.
- Two common ways to think about 2D graphs with 2 independent variables: with 1 independent variable on the horizontal axis, a dependent variable on the vertical axis, and the other independent variable labeling the curve (more common in thermo) OR with both independent variables on the axes and a dependent variables as a surface with levels curves on the graph (more common in E&M and mechanics)

Orient: Imagine that you have water vapor in a container where you can control the temperature of the gas. The temperature and pressure axes show possible values of temperature and pressure for 1kg of water vapor.

1. Without pointing to it or marking it, have one member of your group select an arbitrary location (a "state") on the page.
2. That person should now describe their state in words so that another member of the group can mark it.
3. How many pieces of information do you need to specify the state?

Instructor's guide It may be helpful to give an example of a state on the surface, or a full example of playing this "game".

> **Prep**: Need a contour map with $U(T,p)$ with T and p axes only, no states or other contours.
> **Goal:** Gets at the idea that you only need two variables to specify the state. Cartesian or polar coordinates might come up as another example—talk about how axes in this case have different dimensions — generally true in thermo.

Coordinate: Now imagine you did an experiment where you measured the pressure, p of the water vapor as you varied the temperature, T, for several fixed values of entropy, S, and volume, V, and plotted these curves on the same set of axes. The new contour map shows these plots.

- Locate your state on the new graph.
- Specify your state in as many ways as possible.

> Instructor's guide **Prep:** Need a contour map with $U(T,p)$ with S, V contours, no states.
> **Goal:** Gets at the idea that you can specify the state with any two of the four variables.
> **Note:** Students might try to over-specify the state. Ask how many of the 3 or 4 variables you can independently pick. Maybe as a WCD have 3 groups each specify a different variable

Explore: Choose a second, nearby state and mark it on the graph. In as many different ways as you can, describe how to get from your old state to your new state.

> Instructor's guide **Goal:** Gets at the idea that you need to specify changes in two variables ("constant" is a specified change of zero)
> **Discussion:** How many pieces of information did you have to give to describe a path? Could you have given less information?

Can you find a nearby state where the path involves holding one of the thermodynamic variables constant? 2 variables? 3 variables?

> Instructor's guide **Goal:** Gets at the idea that you can specify one variable to be constant. If you try to specify 2 (or 3) variables to be constant, then the new state is the same as the old state (you haven't gone anywhere).

New Representation: Can you find the states you have been considering on these alternate representations:

1. A rubber sheet that can be stretched and squished so that the S and V contours are straight and perpendicular to each other square.

   > Instructor's guide **Goal:** The set of numbers that describes a state is unique and can be located on different representations of the system.

2. A plastic surface whose height represents the internal energy of the system.

   > Instructor's guide Students will need to be told what the axes represent.

> Instructor's guide **Prep:** Could have a demonstration $U(T,p)$ surface to show students.
> **Goal:** The set of numbers that describes a state is unique and can be located on different representations of the system.