Thinking in Proto

By Kathryn McGuire, Jacob Beal, and other authors of MIT Proto

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Relax, and don't panic. You've found **Thinking in Proto**, a tutorial designed to get you started and demystify the language. Proto is very different from most other programming languages. For most people, even once they've started writing Proto code, it's a big jump to change how you're thinking and really take advantage of Proto's continuous space/time model. This tutorial will hopefully help you make that jump.

Contents

1 Credits for Proto

The Proto language was created in partnership by Jonathan Bachrach and Jacob Beal. As they created the language, Jonathan created the first implementation of MIT Proto, including the first compiler, kernel, simulator, and embedded device implementations. Since that time, Jake and other contributors have built on the work begun by Jonathan.

MIT Proto also includes contributions from (alphabetically): Aaron Adler, Geoffrey Bays, Anna Derbakova, Nelson Elhage, Takeshi Fujiwara, Tony Grue, Joshua Horowitz, Tom Hsu, Kanak Kshetri, Prakash Manghwani, Dustin Mitchell, Omar Mysore, Maciej Pacula, Hayes Raffle, Dany Qumsiyeh, Omari Stephens, Mark Tobenkin, Ray Tomlinson, Kyle Usbeck, Dan Vickery

The Protobo platform code in platforms/protobo/ also includes Topobo-related code from (alphabetically): Mike Fleder, Limor Fried, Josh Lifton, Laura Yip

2 How to Use This Tutorial

In writing this tutorial, we have made several assumptions about you as a reader. First, we assume you are, if not entirely new to programming, entirely new to lisp-like languages and many basic programming statements. If this is not true, and you have worked with lisp-based languages, you will find much of the first sections in this tutorial are easily completed. We encourage you, however, to read the "Using The Proto Simulator" section carefully, as this will be entirely new, and to read the other sections, paying close attention to changes in format from the other languages you may have used. Realize also that though Proto may be similar to other languages, the way of thinking that must be used by Proto programmers is considerably different. Proto allows its user to look at both the individual devices separately, and at the group of devices as a whole. For this reason, we strongly suggest you read the whole tutorial and perform several of the exercises at the end of each section to strengthen your learning.

Second, this tutorial is angled towards programmers using the Ubuntu operating system. Other Unix or MacOS X users should have no problem, as they can use a command-line terminal in the same way. Windows users need to write commands in the command-line prompt on their computer, but the commands should also work in the same manner.

Finally, we assume that you have installed the Proto Simulator and compiler. If you have not, read the information on installing Proto in the **README** file in the Proto distribution. If you have somehow gotten this tutorial without getting a copy of Proto, you can download Proto from the website: `http://stpg.csail.mit.edu/downloads.php`. This tutorial is based off of the Release 2, from 11-11-09, but should work with newer versions of Proto as well.

3 Beginning Proto

Spatial computing is a rapidly expanding field of technology. A **spatial computer** is a collection of computational devices distributed through physical space, in which the difficulty of moving information between any two devices is strongly dependent on the distance between them, and the "functional goals" of the system are generally defined in terms of the system's spatial structure. Most programming languages are stretched from their original purposes and inefficient when applied to meet the needs of spatial computing. **Proto**, however, is specificially designed for programming spatial computers. When trying to program these spatially-embedded systems, it is hard for programmers to work with each device as an individual, and try to figure out how those individual actions combine together. Instead, it is much easier to work with these devices as a whole. Proto is a great way to do this, because rather than taking this space as a problem to work around, it embraces the space as something to take advantage of while programming. If you want to learn more about spatial computing in general, one good source is the web site `http://www.spatial-computing.org/doku.php?id=scw09:start`.

Proto is a **purely functional language**. This means that it uses variables in a mathematical sense and excludes destructive modifications of data: any identifier refers to an unalterable, persistent value. Expressions in Proto are able to be applied to numerous collections of devices over fields of space. A Proto user can use these expressions to perform tasks involving space, time, and movement, both within the MIT Proto simulator and on devices in the real world.

This tutorial uses the MIT Proto Simulator to illustrate all of its program examples. The Proto simulator takes a statement written into the terminal, compiles it, and runs it on a simulated spatial computer. The basic form of a Proto statement written in the terminal is:

```
proto -arguments "(expressions)"
```

Let's test this out. First, go into a terminal or another command prompt (depending on your operating system). Change the directory until you are inside the Proto folder (use the "`cd`" command). Then run the most primitive program one can, typing into the **prompt$** of your terminal:

```
proto "0"
```

It may not seem very exciting, but the dark screen with little red dots you have in front of you is your first Proto program. What's happening? The "`proto`" command reads Proto arguments from the terminal and summons an assortment of devices in the Proto simulator. The "`0`" tells Proto that all of these devices are set to the value 0. The simulator is not directed to display this value, so each device is shown as a simple red point, indicating where it is in space. The next section covers how to use the simulator.

Open the Proto folder. Look for a folder inside labeled "man." The other PDF files inside this folder (**Proto Quick Start**, **Proto Language Reference**, **Proto Simulator User Manual**, and **MIT Proto Developers Guide**) will prove extremely helpful in this tutorial. Be sure to keep track of these and use them when necessary.

4 Using The Proto Simulator

All right, you easily executed that little basic program earlier. Now let's change it up a little. Take that same program you wrote before and add a "`-v`" before the "`0`". Your line in the terminal should look like this:

```
prompt$ proto -v "0"
```

When you run this, the value of 0 is displayed atop the points in blue text. Pull up the **Proto Simulator User Manual**. In this manual are all of the many arguments that you can put in before the expressions to manipulate the simulator display. You can use more than one argument, and some arguments ("`-n`", "`-r`", etc.) will take an integer after the argument to change its value. Without these arguments, their values are set to the default. Try this command:

```
proto -T -n 300 -c "0"
```

Now you see a green web that ties together all of the points. You will notice if you skim the simulator manual and find the "`-c`" argument on page 10 that this argument directs the simulator to display the green network of communication between devices. The "`-T`" is what shows the lavender clocks that tick away unevenly at the bottom of the screen. The right one keeps track of the speed of simulation, and the left one displays a count of simulated "seconds." Why is it not displaying real seconds? This clock runs at the same speed that the computer is able to process information to run the simulator. If the computer is given more information to process, the clock will run at a slower pace. Note that these arguments are case sensitive. Putting "`-t`" here will do something else entirely. The "`-n`" argument tells the simulator the number of devices the user wants to work with. "`-n 300`" directs the simulator that instead of the default 100 devices, we want 300. Execute this again without the "`-n 300`". The network becomes much sparser and the time runs much quicker, because there are less devices to connect and less connections between devices, and therefore less information to process. If the "`-n`" argument is not used, the simulator resorts to the default of 100 devices.

Try this small quiz: add arguments so as to display a network of 10 devices with connections between all of them and their values displayed as 7. Then check your answer below. Hint: this uses one argument we have not used yet.

When you think you have it, look here for our answer. Your code probably looks something like this:

```
proto -v -n 10 -c "7"
```

If it does, you have this down pretty well. However, you might be frustrated with the fact that only a few, or maybe none, of your points are connected to each other. If so, the argument you missed was "`-r`", which sets the distance over which each device can radio to other devices. The devices did not connect because they were too far away from one another to communicate over their short radio-range. Execute this code again, and then press "r" while in the simulator. You should see dim gray circles around your devices.

These show how far these devices are communicating. With the "`-r`" command line argument unused, the default radio range is fifteen meters. Change the range of radio transmission by adding "`-r 100`" to your list of arguments in the terminal. Re-execute. Now all of your points should be connected to one another.

As we have shown by pressing the "r" to show the radio's transmission range, the simulator can be manipulated inside itself as well as at the command line. Many arguments can be switched on and off, points may be moved, and the simulator can be navigated using the mouse and keyboard efficiently from within the simulator.

The **Proto Simulator User Manual** document shows many of the ways that we can manipulate the Proto simulator. Run the program you just built again in the Proto simulator. Press "n." The values go away. If you press "n" again they come back. Leave them off for now. Press "c" and the network also goes away. Press "T" (that's "shift-t,"—remember, it is case sensitive). The timer shows up at the bottom of the screen. Pressing "f" toggles the full screen mode. Now turn the network back on, the timer off, and exit full screen. Left-click on the screen, and drag the mouse. The screen rotates with the mouse. If you right-click drag, you can zoom in and out. To pan, use the arrow keys. Warning: if you pan after you have rotated the picture significantly, the directions may be switched around. Use "z" to reset the view.

Using the Proto simulator manual, try this: make a field of just five points with values of zero and make the "`-r`" range default 15 (or just do not use "`-r`" argument) and display any connections between the points. Your code should look like this:

```
proto -n 5 -c "0"
```

Now use the simulator manual to move all these points so that they are connected. Hint: If you can not find the correct way to move points, try some of the mouse commands on page 4 of the simulator manual. Make sure caps lock is off when manipulating the simulator.

Notice that the green connections latch on to nearby points as you move a device (Figure 1). (In all the pictures in this tutorial, the simulator is displayed with a white background for better printing. Look in the simulator manual under "Palette Files" to find out how to do it yourself.)

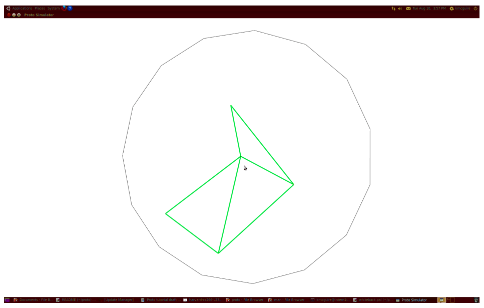


Figure 1: Five connected devices.

Also in the simulator, one can engage three different user test sensors in a device. This way, one can use "`sense 1`", "`sense 2`" and "`sense 3`" points to perform separate actions in a program. For now, lets work on just turning them on and off. Run the original program again:

```
proto "0"
```

Now, click on a point to select the device. Press "t." Remember: case sensitive. It turns the little red dot into a vibrant orange circle. You have just turned "`sense 1`" on for this point. Press "t" again to turn it off. Press "y" or "u" to turn "`sense 2`" or "`sense 3`" on. You can even turn more than one sense in a single device, and if you shift-left-click-drag you can select and toggle more than one device at once. Play around with this to get used to turning these senses on. You have now mastered the basics of the Proto simulator. Use the Proto simulator manual to explore more. Many of the listed arguments we have not yet used will be used later when writing more advanced functions and expressions. Try some of these exercises to enhance your understanding:

Exercises

Exercise 1: Execute a program, adding arguments to the terminal statement so that the little red points will not be displayed and instead only their values will be displayed.

Exercise 2: Execute the same, but do not put any arguments in the terminal code. Instead, toggle these arguments from within simulator. Then kill off three points in the simulator.

Exercise 3: Run a network of 1000 devices. Now run them again with half the expected number of neighbors (there are several ways to do this) and with each simulation step being 0.2 seconds rather than 0.01 seconds (there are ways to speed up the simulator).

5 The Basics

Now that we have a strong hold on the Proto simulator, let's move on to the primary part of the command: the expression. Remember the basic format: `proto -arguments "(expression)"` Proto uses the expression to execute the main tasks of a program. Even with just the "`0`" there, Proto knows to turn all the devices' values to zero. Of course, it is going to get far more complicated than a simple zero. Let's say we want some lucky points we select to be at value one, while the others remain at zero.

One of the ways we can do this is add an `if` expression. Look up an `if` expression in the **Proto Language Reference**. This can be found in your Proto folder in the folder "man." Following the format, let's build a program that asks if "`sense 1`" is turned on, and if it is, have those points' values be one, and the other points' values be zero. It should end up looking like this:

```
proto -v "(if (sense 1) 1 0)"
```

Now the program runs and whenever we turn "`sense 1`" on (select a point and press "t"), the value of that device becomes 1. This works fine, but what if this program was longer, and/or we knew we might use it multiple times? In such cases, we define the function in a separate place and then call on it from the command line. Create a new folder for your own programs inside the Proto folder. I will refer to this folder as the "MyPrograms" folder. Now go into a simple text editor, (one that preferably does not use spell check or auto-correct), and save a new blank document as `check.proto` inside your new folder. Now that you have somewhere to write your program, let's create it.

Firstly, we have to define the function. Look at page 3 in the **Proto Language Reference**; there is a explanation beginning with "`(def`". This shows the reader how to define a function. Following the format, start with "`(def check`" so "check" is the function name, and then give the function its arguments. In this case, we should give it a single argument, `src`, which will designate our source region (in the above case, any point at which "`sense 1`" was true). These arguments allow Proto to take several things as input to a function. In this case, we want it to take whether a device has `(sense 1)` on as its input argument, and store that information in the local variable `src`. So our function definition could be

```
(def check (src) (if src 0 1))
```

Save this code in the text editor, and then go back to your terminal. Make sure you change directories into your new folder. The simulator will only search for functions that are in the terminal's current folder.[1] Then, we can simply call the function by saying:

```
proto -v "(check (sense 1))"
```

It works the same way as before, so what makes this so different from the earlier code? Well, if this program were a lot longer and you wrote it out every time in your terminal, it would not be very efficient for the user at all. By writing programs in separate documents, you can not only call functions multiple times, but you can call functions inside of functions, and in this case, change the `src` of your function to apply it in different cases. This way, you could put inside those parentheses after `check` in the terminal call anything that identifies a set of devices, such as any of the senses, a value, or a function which returns a value.

These `if` statements, other than asking if "`sense 1`" or any of the senses are true (non-zero), can also use **logical operators** and **conditional statements**. Logical operators are used to compare two values in a conditional statement to return a boolean value (true or false). In Proto, like in lisp-based languages, these operators and the numeric operations come before the values in the statements. For example, if we want to ask whether `x` is greater than `y` we must put the "`>`" symbol before the variables, like so:

[1]The simulator has an argument that can cause it to search other places as well. Look it up and see how.

```
(if (> x y) 1 0)
```

Similarly, if we wanted to ask whether `x - 1` is still greater than `y`:

```
(if (> (- x 1) y) 1 0)
```

With some functions (multiplication, addition, etc.), the number of arguments after the operators can vary. Make sure you remember this when you write statements. Because of the difference between `mux` and `if` (described later in the tutorial, in Section 7), there are regular `and`s and `or`s, and `muxand`s and `muxor`s. The descriptions of these are all in the Proto Language Reference. Again, these `and`s and `or`s go before their values.

When using logical operators, make sure all the values that you use are of the same data type. The many data types are listed on page 2 of the Proto Language Reference. For now, we will not have to worry too much about these. Know, however, that the senses return boolean values: either true or false.

Lets try a quick test: Make a function in which if any of the senses are turned on on a device, that device's LED turns green.

You may be thinking *"hold up, LEDs?"* LEDs are commonly used as a debugging tool on spatial computers, since we can look at a lot of devices at once and see an overall pattern. The Proto simulator has the ability to turn on or off simulated LEDs for any or all of the devices in it. Not all devices have LEDs, though, so the function we are going to use is **platform specific**, meaning that it comes from the particular spatial computer we're running on rather than being universally built into the language. Many of the sensors and actuators that we will use are like this. In this case, we are using functions that come from running on the simulator, so they are listed in the Proto simulator manual instead of the language reference.

To turn on an LED, as listed on the bottom of page 9 of the simulator manual, write one of the three colors of the LEDs (red, blue or green), and follow it with an intensity level (This level can also be shown as a physical height above the device).

Go back to your program, `check.proto`, and change the `1` to `(red 1)`. It should look like this:

```
(def check (src) (if src (red 1) 0))
```

Now go back to the terminal and run check again. Now, when you turn "`sense 1`" on at a point, its value does not change to 1, but instead it has a red LED above it. No? That's because in order to display LEDs, you need a new argument before the expression. Replace the "`-v`" with a `-l` (lowercase l), since there is not much use for displaying values in this example. This "`-l`" argument tells the simulator to enable LED display. Your statement in the terminal should now look like this:

```
proto -l "(check (sense 1))"
```

Run the program again. Now when you turn on "`sense 1`", a little red LED turns on above the device. You can also toggle these LEDs on and off by pressing uppercase "L" from inside the simulator. You can turn on multiple "`sense 1`"s and get the red LEDs at more devices.

Now retry the test from above. Hint: The `or` *operator comes in handy. If you are stumped, or if you think you have done it correctly, the solution is below.*

In fact, you do not even have to change the command for this program. Just change your "`(red 1)`" to "`(green 1)`" in `check.proto`, and save the text. Then run `check.proto`, but change the `src` you give into the function from the terminal

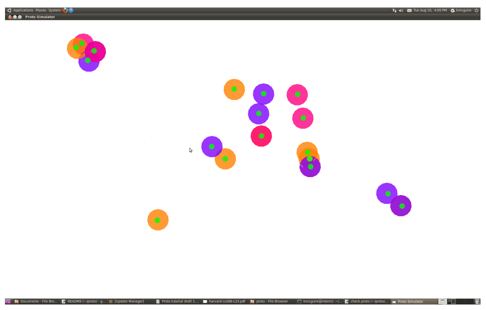


Figure 2: Green LEDs wherever a "`sense`" is turned on.

from "`sense 1`" to include all three senses. You can include all three by using the `or` operator. The `or` operator can only take two values after it, but we can nest the `or`s, so that it takes all three senses into account. **Nesting** is a common practice in Proto, as with other programming languages. Nesting is the practice of placing a function call inside another function call. Nested `or`, `if` and `mux` statements will be common in Proto.[2] Your statement in the terminal should look similar to this:

```
proto -l "(check (or (sense 1) (or (sense 2) (sense 3))))"
```

If you run this and turn on a few "`sense 1`"s, "`sense 2`"s, and "`sense 3`"s (keys "t," "y," and "u"), you should end up with several multicolored circles in your simulator, each wth a green circle at the center (Figure 2). If the program is not working check these things:

- Did you remember to save `check.proto` when you had finished? If not, you are still running the older version of your program. Make sure that the file name ends in ".proto," or else it will not be recognized as a Proto file.
- Does your code look like this: "`(def check (src) (if src (green 1) 0))`"?
- Are you in the correct directory in your terminal, inside the folder where `check.proto` is saved?
- If the simulator exits with a "segmentation fault" error, it usually means you have one too few or one too many parentheses somewhere (it should report a program error to you rather than crashing, but sometimes it's not smart enough yet). Even parentheses around the 0 at the end of the function will cause this error, because it makes Proto think that 0 is supposed to be a function rather than a number. In more advanced functions, it may mean a misconstruction of a `let` or other syntactic construct.
- Is there anything besides your code in the `check.proto` file? The Proto simulator will try to interpret any regular text as Proto code unless it is commented out (covered later).

Once you get this running, congratulations! You have grasped the basics of Proto. In the next chapters we will move on to how we can manipulate three different aspects of Proto: space, time, and movement, in order to succeed in more advanced functions.

Exercises

Exercise 1: Tell the devices to turn on different LEDs based on what senses are turned on.

Exercise 2: Tell all devices to turn on red LEDs, except if any sense is turned on, in which case return different values (2, 3, 4) based on what sense is turned on.

Exercise 3: Turn on a red LED only on a device that has ALL of the senses turned on on it.

6 Thinking About Space

Key Concepts:

- Proto computes with fields, which assign a value to every point in space.
- `nbr*` and `hood-*` functions compute with information from nearby devices.
- `distance-to` measures distance and `broadcast` sends information across space.

[2]Note that Proto is expected to have a multi-input `or` statement in an upcoming release.

Space is a big part of what Proto is about. Most of the programs that you write in Proto will manipulate space, doing things like naming regions of space, measuring distances, and moving information around from place to place. Proto is designed to make this easy by letting you work with *fields*.

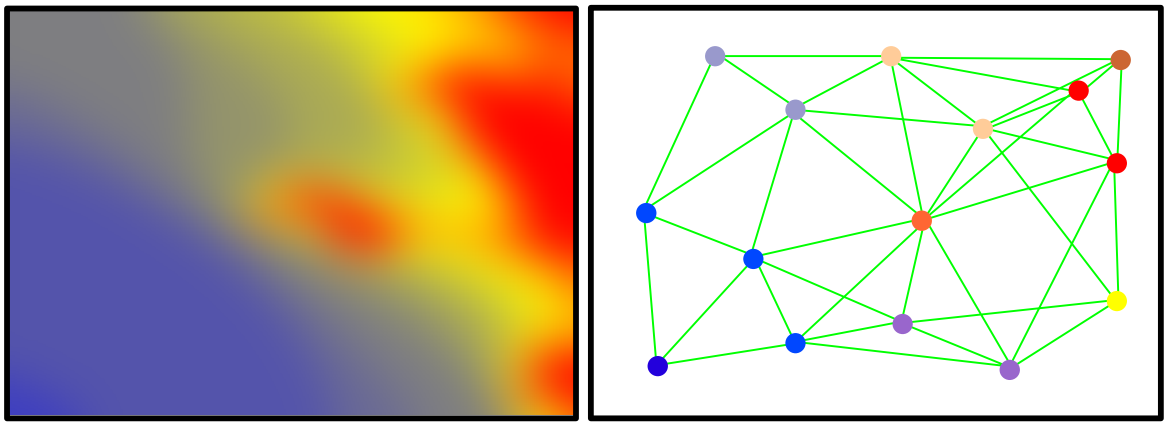

(a) Continuous (b) Discrete

Figure 3: Example of a field: (a) shows a field of temperature in a rectangular room, where warmer is redder. Putting a network of devices into the room, we get a discrete approximation of the field (b), with each device sampling the temperature where it is placed. Devices are shown as circles, with the network connections between them shown as green lines.

A field assigns values to every point in a space. For example, let's say our space is a rectangular room, with an air conditioner over on the left wall and the sun streaming through the windows on the right wall. We can view the temperature in the room as a field: every location in the room has a temperature, and the temperature may be different from place to place. Figure 3(a) shows a temperature field, shading from coldest (shown as blue) to warmest (shown as red). The field is the whole collection of temperature values, each associated with its location.

Of course, we may not get to measure temperature everywhere. If we only have a few devices, and we build our network by scattering them around the room, then we get something more like what is shown in Figure 3(b). Let's look at temperature in the Proto simulator. Go to the demos folder inside the Proto directory. There's a file there called `temperature.proto` that has a simple heat diffusion simulator in it, and another called `temp-color.proto` that will turn the numbers into colors like in our figure. Run them with this command in the terminal:

```
proto -v -l -led-blend "(temp-color (temperature))"
```

The new `-led-blend` argument is blending together the red, green, and blue LEDs into a single color. You should see a few red and blue circles and a lot of yellow circles, with the red and blue spreading out into the yellow nearby as heat diffuses.

Each device measures the temperature at its location, and this collection of samples gives us a discrete approximation of the temperature field. In effect, each actual device is becoming a representative for the portion of the field close to it. This is OK to do because the temperature is likely to not be very different at nearby places, so with only a small number of samples we can get a pretty good approximation of the actual temperature field.

When we write Proto programs, the values we are passing around and computing with are actually fields. Let's think about what happens if we take the temperature and turn on a red LED everywhere that it's greater than 25 degrees Celsius. Run this code in your terminal:

```
proto -l "(red (> (temperature) 25))"
```

You should see some small patches of red that spread out and change slowly as heat diffuses around the network.

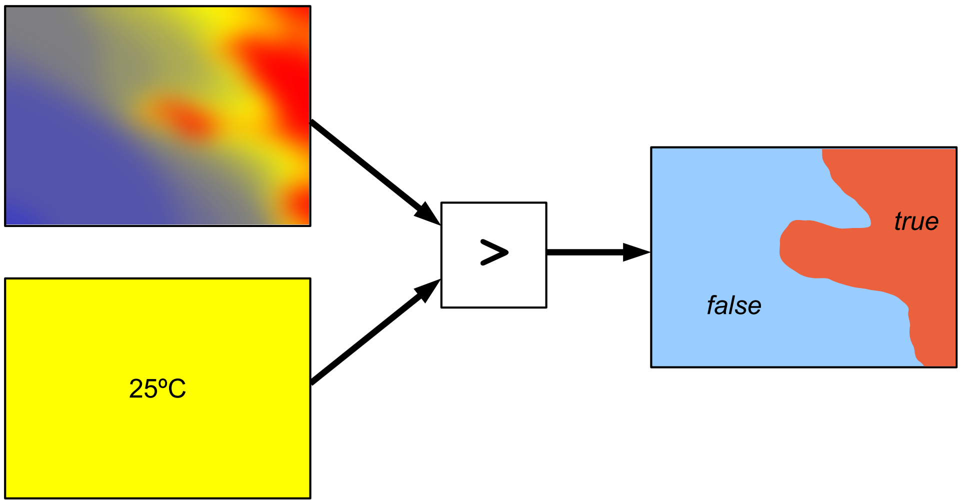


Figure 4: Proto programs compute with fields. For example, if we compare temperature with 25 degrees Celsius, we're really taking a field of temperature and a field of 25s and producing a field of boolean (true or false) values, indicating whether temperature is above 25 at each point in space.

Figure 4 shows the way to think about what's going on in the comparison. We start with our temperature field. We want to compare is against 25 degrees Celsius everywhere, so we need a field that is equal to 25 everywhere. That's what putting the number `25` in our program gives us: it's not just a number, it's a field of numbers, where every point's number is 25. The `>` operator takes these two and computes a field of booleans (true or false): the value at each point is true if the value of temperature field at that point was bigger than the value of the field of 25s at that point, and false if it was not.

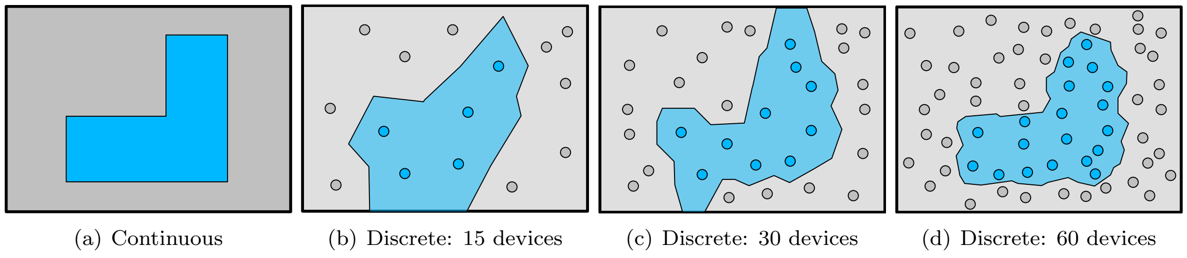


Figure 5: Consider a boolean field indicating where an L-shaped table is (a). When approximated by a small number of devices (b), the field isn't very good at indicating where the table is. As we add more devices (c, d) the field is a better and better approximation.

A field of boolean values like we just computed isn't smooth the way that temperature is: there isn't a "half-true" that goes between true and false. Instead, we can think about the approximation as getting it slightly wrong which parts of space should be true and which should be false (Figure 5). If we keep adding more and more devices, though, our network will look more and more like a perfectly continuous space.

What's important to know is two things:

- The more devices that we have, the better that they approximate space.
- Some programs need better approximations than others, but a lot of programs will work well with very crude approximations.

A big part of the trick of writing good Proto programs is to think about the space, while remembering that it will be approximated.

Now let's start writing some programs that work with space in more complicated ways. Take a look at this code:

```
(def close (src)
  (let ((d (distance-to src)))
    (if (and (< d 3) (> d 1))
      (blue 1)
      (blue 0))))
```

There are several new things in this code. For instance, the `let` (which you surely recognize if you have used lisp programming before). This `let` assigns the variables inside it to new values. In this `let` statement, `d` is set as the distance to the source. The function `distance-to`, as its name suggests, gives each device its own value of estimated distance to the source. You can look up these functions in further detail in the Proto Language Reference. Put this program into a new blank text document and save it into your programs folder as `close.proto`. Call it with this in your terminal:

```
proto -l -n 1000 "(close (sense 1))"
```

Remember that "`-n`" sets the number of devices, which means this program has 1000 devices to work with. Now `src` is set to `(sense 1)`, so if we execute this program, and turn on "`sense 1`" for a few devices, you will see that only devices within a very small select range from the `src` turn on their blue LED. If you turn on "`sense 1`" on a fairly isolated device, you might not have any of the surrounding device LEDs turn blue at all. The program tells each device to figure out their distance to the "`sense 1`" device, which they should call `d`, and that if their individual value of `d` is less than three meters and greater than one meter, then they may turn their LEDs blue. Otherwise, the LEDs remain blank `(blue 0)`. Try expanding this range of blue LEDs by increasing the first parameter of the `and` statement (remember to save and re-execute your code to try the program).

This is all good and fine, but what if we wanted to be more precise in our selection? What if, instead of taking three points or no points, based on how close the randomly placed points were to the src, we wanted just a single closest point, no matter how far or close it is to the src? This is where the `nbr` and the "`hood`" functions come in. These functions are used to tell a device exactly where each point within its communication range is relative to itself and what values these neighbors have calculated, giving the device fields of points and values to work with. Using these functions, we can select the point(s) that we want accurately. This function demonstrates that:

```
(def closest (src)
  (let ((d (distance-to src))
        (min-d (broadcast src (min-hood+ (nbr (distance-to src))))))
    (if (and (not (= min-d (inf)))
             (= min-d d))
      (blue 1)
      (blue 0))))
```

This code is built to light up the device LED that is closest to the `src` (source) blue, and it introduces a wide variety of new functions. Let's walk through how to make it, step by step. First, create a file called `closest.proto` inside your folder in the Proto directory. Inside that, define the function `closest` as a function that takes argument `src`.

We see our `let` function again, except this time it defines two separate variables instead of just one. The first one we know already: variable `d` is the distance to the source device. The second definition is where most of the confusing bit comes in.

We are trying to assign the value of the shortest distance to the source to our new variable `min-d` (minimum distance). Let's work from the inside parentheses out in this definition. First, we have our `distance-to src`. Note that you cannot use the predefined `d` here, because `let` defines everything at once, and so Proto will not recognize this variable as being already defined. Later, we will cover how to use the `let*` function to sequentially define variables. Now that each device has established its own distance value (which happens to be the same as `d`). The `nbr` function gathers up these values from each device's neighborhood, returning a field that maps each point in the neighborhood to a distance value. All the functions starting with `nbr` in the Proto Language Reference create fields of values assigned to neighboring devices. In fact, instead of putting `(nbr (distance-to src))` here, one could instead put `(nbr-range)`, which again assigns a field of distances to neighbors, with the same outcome since for this program we only care about neighbors of the `src`. The `min-hood+` function takes all of these values returned by `nbr` as pairs, (neighbor, distance away), and then takes the minimum "distance away" value as its return value. This is important: because of the "`+`" at the end of `min-hood`, the device excludes its own value from the calculation.

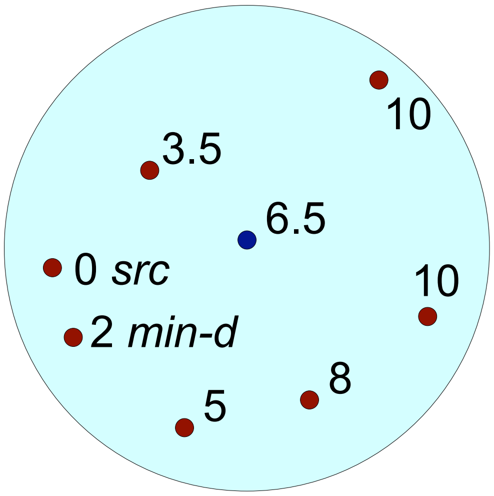


Figure 6: Field of `nbr` values of `d` for a device (dark blue) near a `src` device.

Were this not the case, the closest device to itself would always be itself. If you examine page 11 in the Proto Language Reference, notice that most of the neighbor summary functions allow for this "`+`" differentiation.

The broadcast function sends information from the `src` devices to all of the other devices. If there is one `src` device, then every device ends up with the same value; if there is more than one `src` device, then every device ends up with the value from the nearest `src` device. Here, in our `closest` function, we are using broadcast to have the `src` tell every other device what the closest device to itself is. Every device computes the `min-hood+` expression, to find out how close is its closest neighbor (besides itself) to the source. Only the `src` devices send the value.

The main part of this function, (after the `let`) is actually quite simple. All it does is have each device ask itself, "Is my distance to the source equal to the minimum distance to the source, and is the minimum distance to the source not infinity? If so, turn LED blue; if not, leave LED blank." This part: `(not (= min-d (inf)))` stops the devices from automatically turning blue, because before any source is identified, the minimum distance to the source is infinite, and all the devices' `d` variables are also infinite and therefore equal to `min-d`. This test tells the program to wait until a `src` exists, which will cause `min-d` become finite. Remember that if you want to look over any of the `nbr`, `hood`, `broadcast` or `not` functions, or even how to use constants such as `inf`, you can find them all in the Proto Language Reference.

This is how to call the `closest` function in the terminal, much like the `close` function:

```
proto -l "(closest (sense 1))"
```

When executed, this produces a field of devices, shown as little red dots. Right now, all the devices know that `min-d` is equal to infinity, and therefore all their LEDs are off. Turn "`sense 1`" on on any device. After a few seconds, a blue LED goes on on the closest device to the `src`, no matter how close or far that device may be. You can turn "`sense 1`" on or off at several devices, and their closest neighbors' LEDs will turn on or off accordingly, since the `broadcast` is taking the value from the *nearest* source (Figure 7). Take note, however, that if you isolate a "`sense 1`" device to the point that all other points are outside of its radio-range, no `min-d` can be found. Also, turning on two "`sense 1`" devices close together may allow only a single `min-d` value (depending on where exactly the closest neighbors are), so only one of the sensed points may light up its closest neighbor. Similarly, if a "`sense 1`" device is with direct communication range of another "`sense 1`" device, both will light their LEDs, since they both see the other being zero distance from the `src`.

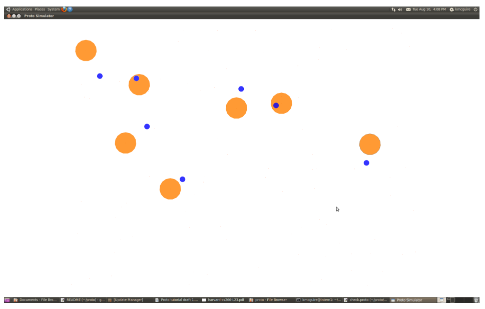


Figure 7: Running the `closest` program

Try this test: Write a program in which all the points create a bullseye target-board using LEDs. You don't have to use any `nbrs` *or* `hoods` *for this program. Remember to refer to the Proto Language Reference whenever you get stuck. You can do this any way you like with any colors you like. Remember, 100 points don't create much of a bullseye, so use the* `-n` *argument to create more points (1000 points should work well). If it seems complicated, you are probably over-thinking things. Hint: Nested* `if`*s may prove helpful.*

When you're finished, look here for the answer. Our code, which may differ from yours some, looks like this:

```
(def bullseye (src)
  (let ((d (distance-to src)))
    (if (< d 15) (red 1)
        (if (< d 30) (green 1)
            (if (< d 45) (blue 1) 0)))))
```

and I call it with this command:

```
proto -n 1000 -l "(bullseye (sense 1))"
```

Again, this uses the `let` and `distance-to` functions, and sets `d` to the `(distance-to src)`. Then each device asks itself whether it is within 15 units from the source, between 15 and 30 units from the source, or between 30 and 45 units from the source, and then sets its LED color accordingly. If it is in none of these three ranges, no LED will turn on, and it just returns zero. This text should again be saved in a file in your folder in Proto, as *`itsname`*`.proto`. The name of the file before `.proto` should be the same (capitals and everything) as the name of the function. So in this case, the file is called `bullseye.proto` and is in your "MyPrograms" folder.

To call this program, I changed the number of devices to 1000, so it could be clearly seen in the Proto simulator. You can use more devices, but remember, the more devices you use, the slower your program begins to run. After 5000 or so devices, this program works very slowly, if at all. You can, however, speed up the simulator with the `-s` argument (find this in the Proto simulator manual). I also recommend that you begin saving your terminal call statements *inside* your program text file, so you know how to call the program in future use. Just make sure that if you do, you add a ; in front of it, which will comment it out so that Proto does not read it as it is reading the file. You should do this with anything you add to your Proto files that you do not want to be executed. It is good practice to add descriptions of your code in this way also. When this program executes, it fills the simulator with 1000 little red devices. When I put a device on "`sense 1`" that is approximately mid-screen, red dots begin to fan out, and then green, and then blue. Eventually the LEDs form a pretty nice target-board.

One can use these functions using distance, `nbrs` and `hoods`, incorporated with movement and time functions to create all sorts of useful Proto programs involving space. You now know enough to create many geometric patterns in Proto.

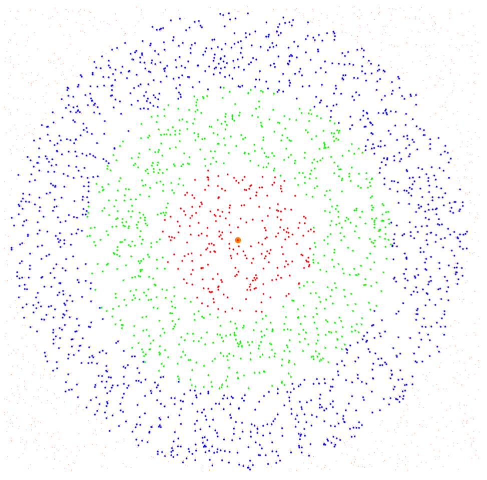


Figure 8: Running a `bullseye` program

Exercises

Exercise 1: Adjust the "`bullseye.proto`" program to make the LED lights be at a height above the device based on the distance to the source. Remember, in `(red 1)`*, the* `1` *sets a height for the LED to be displayed.*

Exercise 2: Create a program in which any device that is on the shortest path from a "`sense 1`*" device to a "*`sense 2`*" device turns its LED green.*

Exercise 3: Adjust the previous program so that the points within the path also turn their LEDs red if they are close to the "`sense 1`*" or sense "*`2 points`*" (within 5 meters).*

7 Restricting Space

Key Concepts:

- Thinking about *where* a program is running is essential.
- An `if` branch changes where a program runs; a `mux` branch lets two branches share information.

When we write a Proto program, we aren't just stuck to using the same space that we started with. We can change the space so that the program runs on just one part.

You've already seen the function that will be used to do this. The `if` function actually works by restricting the space that each of its two sub-expressions runs in. For example, try running this program in your terminal:

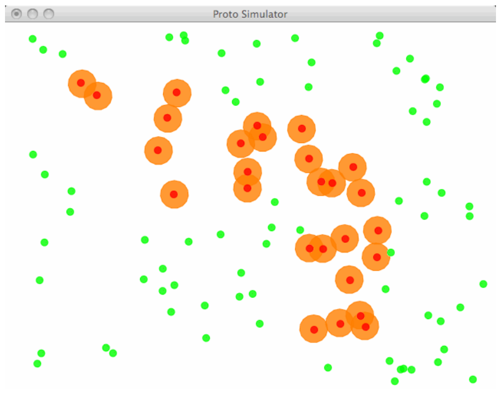
```
proto -l "(if (sense 1) (red 1) (green 1))"
```

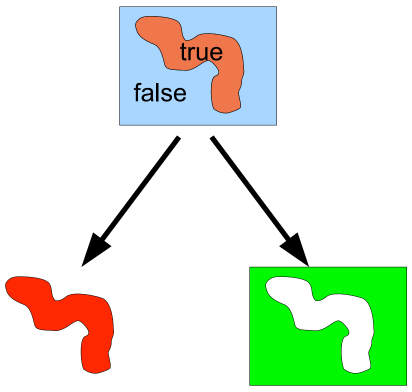
Anywhere that you turn on "`sense 1`", the red LED turns on and the green LED does not. Everywhere that you don't turn on "`sense 1`", the green LED turns on and the red LED does not. Thought about in terms of individual devices like this, what is happening is fairly intuitive.

We can also think about this program in terms how it is acting over the whole space at once. In this view, the `if` is actually changing *where* the program runs. Ordinarily, when we write a piece of Proto code, it runs everywhere at once. When we wrap a piece of code in an `if`, it splits the space into two parts. In the part of space where "`sense 1`" is turned on, it runs the program that turns on the red LED. In the other part, it runs the program that turns on the green LED. This way of thinking about running a Proto program may be less intuitive, but thinking about it this way will help to understand more complicated programs.

Let's use our new understanding to think about how `if` should interact with computations over space. When we use functions like `distance-to` or `broadcast`, they are not doing their calculations by magic: each of these functions is a computation over the devices in our space, built out of simpler functions like `nbr` and `min-hood`. This means that changing the space with an `if` will change what the function computes.

Try using your new understanding of how `if` changes space to predict what will happen when you run this program:


(a)



(b)

Figure 9: When `if` is used to choose which LED to turn on (a), it splits the space into two parts and runs each branch only in its own part.

```
proto -l -c "(if (sense 1) 0 (red (< (distance-to (sense 2)) 100)))"
```

When you run the program, try turning on "`sense 2`" at a device and then turning "`sense 1`" on and off for groups of nearby devices. Did you guess what would happen? The "`sense 1`" devices act like blockages, making the distance measurements computed by `distance-to` flow around them. It's as if those devices aren't there at all—and because of the `if`, that's exactly what it looks like to the part of the program running `distance-to`!

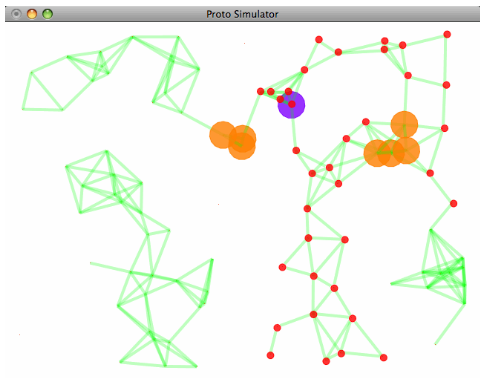


Figure 10: A `distance-to` calculation running restricted to one branch of an `if`

Sometimes we want to be able to split up our space like this, and sometimes it is a problem. For example, let's say we want to make our devices play the "hot and cold" guessing game. A few of the devices will secretly decide that they are the targets of the guessing game. We will make a guess by turning on "`sense 1`" at a device. The device will turn on a green LED if we guessed right, a red LED if we're close to a target, and a blue LED if we're far away from all the targets.

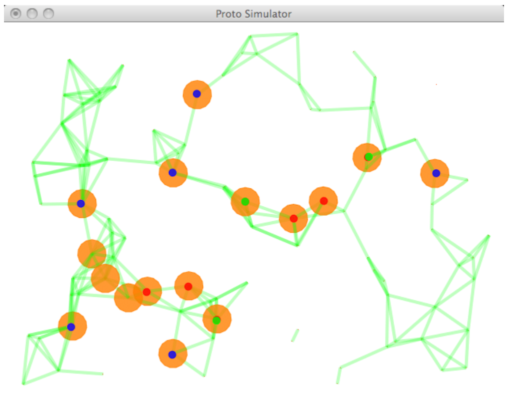
Here's some Proto code to implement the "hot and cold" game:

```
(def hotcold ()
  (let ((target (once (< (rnd 0 1) 0.03))))
    (if (sense 1)
      (all (green target)
           (red (< (distance-to target) 25))
           (blue (> (distance-to target) 50)))
      0)))
```

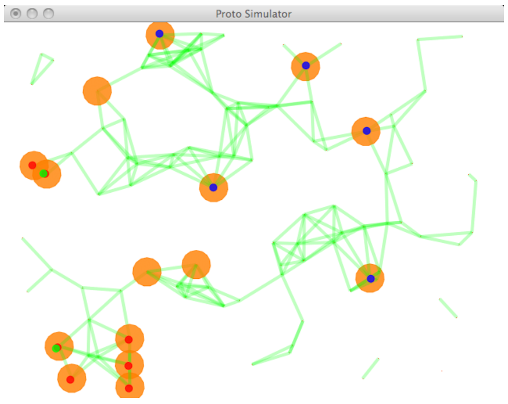
All of the functions in this code should be familiar except for `all` and `once`. The `all` function takes any number of expressions and runs them all, then returns the value of the last one. In this case, we're using it to check whether each of the three LEDs should be turned on. The `once` function computes its expression just once, then remembers the value—we'll learn more about how it can work in the next section. Here, we're using it to have each device flip a coin and decide if it's once of the targets. We do it with `once`, because we don't want the devices to keep flipping coins and changing their minds.

Put the program in `hotcold.proto` and try running it with:

```
proto -l -c "(hotcold)"
```



(a) Wrong



(b) Correct

Figure 11: A "hot and cold" game running incorrectly (a) and correctly (b).

Do you notice something wrong with how the program is running? It's really hard to find the targets! When you make a guess, it almost always shows up blue. In fact, you can't get any to show up red until after you find a target, and then all of a sudden a whole bunch of blue LEDs turn red! And even once you've found a target, the devices nearby won't necessarily end up with the right colors. What's happening here?

You guessed it! The problem is the `if` that we are using. When the program branches on "`sense 1`", that is changing the space where the LED calculations are running. Rather than running everywhere, they run only on the devices where we have already made guesses. Why is this so bad? Think about what happens if you guess a device that's right next to one of the targets. When we run the `distance-to` function on that device, it uses `nbr` and `nbr-range` in order to figure out how far it is from the nearest target. You should think about `nbr` not just as a device getting information from its neighbors, but also as *sharing* information with its neighbors. So if a device isn't in the same branch of an `if`, it won't share its information. Even though there is a target right next door, unless we've already guessed the target, the target won't be sharing information in the `distance-to`, and the device we just guessed at won't be able to tell that it's close.

For this reason, there is another type of branch in Proto. This function is called `mux`, and it works just like `if` except that both branches run everywhere. This is a very useful tool for us, because it lets the two branches share information back and forth if they want to. Now, the test expression is used to pick which branch gives the final value of the functions, rather than picking where each branch runs. We need both `if` and `mux` branches: sometimes we will want to stop information from flowing and will use `if` and other times we will want to share information and will use `mux`.

Let's try this out: try rewriting the "hot and cold" game using `mux` *instead of* `if`*.*

When you're finished, look here for the answer. Our code, which may differ from yours, looks like this:

```
(def hotcold ()
  (let ((target (once (< (rnd 0 1) 0.03))))
    (green (mux (sense 1) target 0))
    (red (mux (sense 1) (< (distance-to target) 25) 0))
    (blue (mux (sense 1) (> (distance-to target) 50) 0))))
```

Try running this version, using the same terminal command as before, and see that it's now working correctly. When you tried fixing the `hotcold` program, you might have had a hard time getting the LEDs to not turn on until you hit "`sense 1`". If that happened to you, it's because `mux` is running both branches, not just the one that gets picked in the end. So if you run "`(mux (sense 1) (red 1) (green 1))`" you'll always have both the red LED and the green LED on!

You now understand one of the trickiest bits about thinking in Proto. When we write our programs, we're not just computing over space, we're changing the space where we're computing. If you think carefully about *where* your program is running, you will always be able to understand what is going on and how to get your programs right.

Exercises

Exercise 1: Fix the `hotcold` *program without using* `mux`*.*

Exercise 2: Create an "intersection of bullseyes" pattern. Use two sources, and around each source create a bullseye pattern with a radius of 45 meters. Only turn on LEDs in the overlap between two bullseyes overlap, and only turn on the LED for the father distance. When the sources are on top of one another, this should produce a perfect bullseye, and when they're barely close enough to intersect it should produce a thin perpendicular patch of the outermost color.

Exercise 3: Calculate how far every device in space is from "`sense 1`*", if we restrict travel to only those locations within 20 meters of "*`sense 2`*" and more than 50 meters from "*`sense 3`*"*

8 Thinking About Time

Key Concepts:

- Proto programs remember information over time using `rep` and `letfed`.
- Programs that act over long distances are made by wrapping a neighborhood computations in a `rep` or `letfed`.

In Proto, as with any programming language, time is an important part of its programs. We have already seen how to display the Proto simulator's main clock at the bottom of the simulator screen. This clock is always running whether or not we choose to display it, counting how many simulated seconds of time have gone by. We know that in Proto, our timers, like this one, will not run in actual seconds, but will run at whatever rate Proto is managing to run through its program.[3]

Now we will start working with time directly in our programs as well. Let's start by setting a simple timer on every device. Call this inside your terminal:

```
proto -v "(rep t 0 (+ t (dt)))"
```

When it executes, you will see a hundred devices timing things at various "second" lengths. Some display nine seconds while others display seven or ten. They have different values because each device is running its own independent internal clock, and these clocks are not necessarily synchronized with one another. The program is being run in rounds, once per second. Every time a round is run, the program's value changes.

To display the discord between devices clearly, run the program again, this time setting the number of devices to five and changing how much the devices differ from one another:

```
proto -v -n 5 -desired-period 0.3 -desired-period-variance 0.1 "(rep t 0 (+ t (dt)))"
```

[3]The simulator has a command line option to keep simulator and actual time synchronized. Can you find it?

With only five devices, you can more easily watch how the timers run at different rates. Turn on the timer at the bottom of the screen (press capital "T" while in the Proto simulator). Notice that all the devices' timers still manage to stay with around the same value as the overall simulator time shown on the bottom-left corner of the screen. To see this more clearly, you may want to pause the simulator and step its time forward in small increments: press "s" to step and "x" to resume fast execution.

There are a two new functions in here: `rep` and `dt`. Both are defined on page 5 of the Proto Language Reference. Take a look at the form of `rep`. The `rep` function creates a variable, just like `let`, but the variable created by `rep` is used to remember information from round to round of the program. In this case, we use the function `rep` to create the feedback variable `t`, which will store elapsed time and has the initial value of 0. The third argument, "`(+ t (dt))`", tells the how the value changes over time—how it "evolves." In this case, Proto reads that every time it runs through this code, it should add one `(dt)` to the current time. What is one `dt`? This `dt` value is the amount of time elapsed between rounds in a program. So we essentially add the time of one round every time we go through a round. The whole `rep` expression then returns the value of `t`. We can also make more complicated feedback functions using `letfed`, which can make more than one feedback variable and allows you to use them in a further part of the program just like variables from a `let`.

Let's say our field is a giant collection of microwave ovens. Do we want our microwave timer running all the time, and on all the machines? Of course not. Let's try put some limits on our timer. We only want this timer to run on the microwaves that are turned on. Create a file with this function in a new file in your programs folder:

```
(def MWTimer (src)
  (if src (rep t 0 (+ t (dt))) 0))
```

Make sure that you save it correctly inside the Proto folder. Then run it from the terminal. Try this call from the terminal on your own. Tell the simulator to show the values, and put the source in as "`sense 1`". You may also want to use five to ten devices instead of the normal hundred, to run the program fast and be able to see what's going on at each device more easily.

When the program executes, turn "`sense 1`" on for one of the devices. A timer begins to run on that device (though our microwaves are counting seconds up instead of down, the way that ordinary microwaves do). Turn it off and the timer shuts off and returns to zero. Turn it back on again and it starts counting up from zero. This is because the `rep` function is inside the branch of an `if`. When we turn off "`sense 1`" for a device, the `rep` expression stops being run and so `t` stops existing on that device. When we turn it back on, there's no old value of `t` for it to evolve from, and so it has to start all over again with the initial value.

Now let's assume that you have just taken the soup out of the microwave out for a moment, to see if it is hot enough. It's not, so you put it back in, and want the timer to start up right where you left off. With this program, that would not work, and you would have to start it again from zero. To fix this, let's change the "evolve" part of the `rep` function (see page 5 of the Proto Language Reference), so that that this function does not restart every time, and so that `t` stays at its new value when the timer is not running, rather than going back to zero. Here is our code:

```
(def MWTimer (src)
  (rep t 0 (if src (+ t (dt)) t)))
```

This code is very similar to the original program. All we did is take the `rep` function out of the `if` statement, so that each point is keeping a `t` value, but the source is the only device whose `t` value "evolves" upward as a timer. All the other points stay at their unchanging values of `t`. Run this in your terminal, again displaying the values with the "`-v`" argument, and setting the number of devices to about five or ten. When the map of devices shows up, turn "`sense 1`" on on any of the devices. Turn it off again, and it retains its current value. Turning it on allows it to resume the count from the same point. Remember, you can set this timer on multiple devices, and it will work in the same manner, since each device has its own value of `t` in its own memory.

Okay, let's try a test that uses both time *and* space. A police station has gotten a call that there is an emergency in the very farthest house away from their station. They need to reach the site of the emergency within twenty seconds or the situation will worsen considerably. Build a program that sets a timer on the very farthest device from the source (the station), and turns this device's LED to blue. When the timer reaches twenty seconds, have this LED switch to a bright red. Again, if you need help with some of the functions, the Proto Language Reference will prove a helpful tool. Note: if you have the devices display their values, the program slows down considerably since drawing text is slow; to speed the program up, either don't display the values or use the "`-s`" command to make the simulator take larger time steps between each time it draws.

Accessing the farthest point is a little more complicated than your closest program, because the farthest point will not be within the source point's range. You will more than likely be tempted to simplify this task by just extending the communication range so only the source and the farthest point will communicate. However, this is impractical for real-life situations. Instead, you should combine `nbr` and feedback to pass values from device to device in a series of "hops." At each hop, your `nbr` operation moves information from one device to another and your `rep` or `ledfed` feedback operation remembers the information so that the device can pass it on for the next hop.

Here is our code:

```
(def emergency (src)
  (let ((d (distance-to src)))
    (letfed ((max-d
              0
              (max (if (< d (inf)) d 0) (max-hood (nbr max-d)))))
      (if (and (< d (inf)) (< (abs (- max-d d)) 10))
          (let ((timer (rep t 0 (+ t (dt)))))
               (if (>= timer 20)
                   (red 1)
                   (blue 1))))
      0))) ; Don't need to do anything: LEDs shut off if not triggered
```

This brings use to one of the hardest ways of thinking in Proto. We have to be able to shift our thinking back and forth between what is going on for the space as a whole and what is going on at each individual devices. Imagine our field of devices. The devices are all originally thinking, "I am the farthest point," because they have not yet been informed otherwise. All their values of `d` are infinite, because either a source has not yet been established, or they have not yet learned the source from their neighbors. Then, suddenly they learn their value of `d`. They evolve their value of `max-d` to be either their value of `d`, or the maximum of their neighbor's values of `max-d`, depending on which is larger.

Thinking about the group, devices look in their neighborhoods for the highest values of `d`, and then compare those to their neighbor's highest values. Each neighbor is in turn comparing values with its own neighborhood, all the time raising `max-d` to the highest values found, so that this information keeps spreading from neighbor to neighbor like a continuous ripple until the highest value of `max-d` is communicated to all the devices. This sort of information-spreading process is often called **gossip**, which makes sense because information spreads indiscriminately in all directions. It's even more appropriate because once a piece of information like a a high `max-d` value is out there, there is not way to retract it and lower `max-d` again.

Now, thinking about it in literal code, we know `d` is set as the distance from every device to the source. The `letfed` function establishes a variable (`max-d`), and initializes it to zero, and continuously evolves `max-d` every step with the next section of code. The `max` function takes the higher of the two values that follow it. The first expression returns `d` unless `d` is still infinite (the device's own estimate, once it has one), and the second expression returns the maximum value of the neighbor's values of `max-d`. After this `letfed` function has evaluated several times in each device, each device will have found the `max-d` to be the farthest distance to source.

This type of pattern, where we wrap a neighborhood computation in a `letfed` or `rep`, is very common in Proto programs. This is always how we build programs over long distances. The neighborhood computation moves information around locally, and the `letfed` or `rep` remembers the information so that it can be passed on to other neighbors. For example we can build a simplified version of `distance-to` like this:

```
proto -v -c "(rep d (inf) (mux (sense 1) 0 (min-hood+ (+ (nbr-range) (nbr d)))))"
```

This program is really just applying the triangle inequality, which you probably remember from geometry class: the shortest distance between two points is no longer than the distance through another point nearby. So here the `sense 1` devices are our source, that always have distance zero. They store this in their distance estimate, which gets named `d` and share their `d` value with neighbors—notice that we have to use `mux`. Their neighbors measure how far they are away, add zero, and take the smallest for their own `d`. It goes on outward like that through the network, with each device estimating its distance by looking for the shortest distance through a neighbor. We thus build programs that "chain" information from neighbor to neighbor, spreading throughout the whole space. This is a very powerful idea, because if we build the neighbor calculation in terms of continuous units like meters and seconds, then it doesn't matter how big the neighborhoods are, just whether it's possible to get from one area to another.

In the `emergency` program, we have the farthest point identify itself by asking, is the value of `max-d` equal to my `d`? However, saying this directly will not work. Why? Imagine the field again. The farthest device has finally established its distance to the source through communication with the devices that form its path to the source. It adds its distance to the first device on the path, plus that device's distance estimate. That device's distance estimate is its distance to the second device on the path, plus the second device's distance estimate, and so on along this path. Let us imagine the farthest device comes up with a value of 160 as its distance to the source. All the devices in the network now take this value as `max-d`. But wait! The devices aren't all running synchronized and some late-arriving information shows up. Now the farthest device realizes that indeed, this path through these devices to the source is not as straight and therefore not as short as the shortest possible path. The shortest possible distance through the new path is 155, so `d` is changed to 155. But all the neighboring devices are still telling it that `max-d` is 160, and it can't tell where that information came from so it thinks it is not the farthest device. In the version of `emergency` above, we use `(< (abs(- max-d d)) 10)` as a kludge to allow the devices a margin of error. However, this is a rather sloppy and unreliable method. There is a much more accurate way to do this:

```
(def emergency (src)
  (let* ((d (distance-to src)) (dis (if (< d (inf)) (once d) 0)))
    (letfed ((max-d
              0
              (max (mux (< dis (inf)) dis 0) (max-hood (nbr max-d)))))
      (if (and (< d (inf)) (= max-d dis))
        (let ((timer (rep t 0 (+ t (dt)))))
          (if (>= timer 20)
              (red 1)
              (blue 1)))
        0)))) ; Dont need to do anything: LEDs shut off if not triggered
```

Here, we establish another variable, `dis`, as the first value of `d` that is less than infinity. Now we instead use `dis` to establish `max-d` among the devices. This way we are comparing the circulating values of `max-d` to the original distance estimated by a device, rather than the alterable values of `d`. This is still a trick, because it is not taking the most accurate values of `d`, but it will at least always choose some device as the likely farthest.

Can you come up with a way to always correctly find the farthest device using the most accurate values of `d`*?*

After the farthest device identifies itself, it sets a timer and names it in the inner `let` function. The timer is now ticking away invisibly in the farthest device. Each step, the devices check whether this timer's value exceeds twenty seconds. When it does, it lights its red LED. Until then, a blue LED is lit. Execute this with this code in your terminal:

```
proto -l -n 1000 "(emergency (sense 1))"
```

Remember, we use these command line arguments to display LEDs and to set the number of devices to 1000. Then turn on "`sense 1`" on any device. You will soon see blue dots fan out through the points, until there are just a few dots lit around the edges and in the corners. Eventually they wink out leaving a single blue dot. Wait (roughly) twenty seconds more, and the LED of that device turns red.

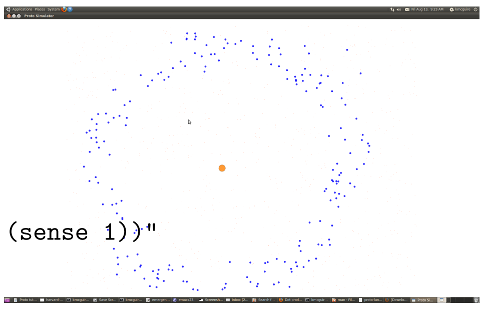


Figure 12: The `emergency` program searching for the farthest device.

This program works fine for the use it is set for, but if you were the police chief, it is unlikely you would be told you had exactly twenty seconds to reach an emergency. You would make that determination based on what situation you were told was the emergency. So let's change this function just slightly. Instead of setting the time in the function to an automatic twenty seconds, we will let a value for time be input into the function from the terminal. Up to this point in the tutorial, we have only used a single argument in our functions (`src`), but we are allowed to use as many function arguments as we need.

Let's add the argument `TimeTilUrgent`, and change our number of seconds, 20, to the variable `TimeTilUrgent`. Our function now looks like this:

```
(def emergency (src TimeTilUrgent)
  (let* ((d (distance-to src)) (dis (if (< d (inf)) (once d) 0)))
    (letfed ((max-d
              0
              (max (mux (< dis (inf)) dis 0) (max-hood (nbr max-d)))))
      (if (and (< d (inf)) (= max-d dis))
        (let ((timer (rep t 0 (+ t (dt)))))
          (if (>= timer TimeTilUrgent)
              (red 1)
              (blue 1)))
        0)))) ; Dont need to do anything: LEDs shut off if not triggered
```

When we call the function from the terminal:

```
proto -l -n 1000 "(emergency (sense 1) 20)"
```

The `TimeTilUrgent` argument is set again to twenty seconds by this call, but it can now be set as any numeric value. We can also change our timer to measure the progress of something other than seconds. For example, it might measure how much fuel is left in an emergency power generator running at a medical clinic, and we need to get there before the fuel runs out and leaves the clinic without power. If the generator burns 1 gallon of fuel every 5 minutes, then we can change `TimeTilUrgent` into `GallonsTilUrgent` and change `dt` to the appropriate fraction of itself: `(/ (dt) (* 5 60))`. Thus, each second the timer advances by 1/300th of a gallon, measuring expenditure of 1 gallon every five minutes. In this way, we can change the way our timer runs to match the problem that we are solving.

As the programs used in this section demonstrate, time is a valuable aspect of Proto. Play around with the functions you have learned so far to do a few test programs. Set a task for the program to perform, and attempt to reach that goal using your new hold on the Proto Language. Remember to use the ever-helpful Proto Language Reference.

Exercises

Exercise 1: Modify your microwave timer program to count down, like a normal microwave. Then change the inputs, so that you add one minute to the timer every time the user turns "`sense 1`" on (i.e. if the user toggles "`sense 1`" three times, the microwave should run for three minutes), and pause the timer whenever "`sense 2`" is on.

Exercise 2: Create a field of 10 points. Have them all turn on timers. If the timer, rounded to the nearest second, is at a multiple of three, have it turn its LED red. If the timer is a multiple of three with a remainder of one, turn the LED green. Else turn the LED blue. Make sure that your program works when the time step is fractions, as well as whole seconds.

Exercise 3: Create a program in which a timer begins in a "`sense 1`" device. Devices whose distances from the "`sense 1`" device are less-than the value of the timer should turn on their red LEDs (e.g., when the timer reaches 10 seconds, devices within 10 meters from the source turn on red LEDs).

Exercise 4: Write the `once` function, which takes in an expression and remembers the first value that expression has, no matter what it changes to later.

9 Moving Devices

Because Proto uses a network of numerous devices to perform diverse tasks, controlling group movement is essential to building for mobile devices in Proto. Movement functions may tell devices to move towards or away from other devices, to follow a leader, to cluster in groups, and more. These functions allow users to apply time and distance functions in new ways with new results. Movement functions are invaluable to the Proto programmer who wants to use movement in spatial computing. Why don't we start by dissecting this example:

```
proto -m "(mov (if (sense 1) (tup 3) (disperse)))"
```

This program is one of the simplest one can do using Proto movement. The new parts:

- `tup`: "tup" is short for tuple, one of the data types we have not used before. The `tup` function takes the values it is given and puts them into a short list. When all of the values are numbers, this is a vector, which can specify a speed and direction in space. Generally, the first value this vector is given is its length along the x-axis; if it is given a second, that is its length along the y-axis. It can also be given a third for the z-axis if we use the 3D mode of the simulator, which will be covered later. Any values we don't put in the vector are assumed to be zero.
- `mov`: this function, as shown in the Proto language reference, takes a vector and uses it to determine the velocity of a device—the speed and direction that the device is traveling.
- `disperse`: this is a separate function that computes a vector to each device, so that if the devices follow their vectors, they will move away from other devices within their radio-range. This function will vary with different radio-ranges, because the devices will only disperse from the devices they are communicating with. Look at the Proto Language Reference for more information on the `disperse` function.

Execute this function. The Proto simulator displays 100 devices. After a moment, they begin moving about, and you soon have to zoom out (mouse scroll backwards) in order to see all of them on your screen. Eventually, they become semi-evenly spaced, wavering just a bit to one side or the other as they push each other out of communication range. Now, interrupt this peace by mass-selecting (click and drag over an area) a group of devices on the left side of the device map. Then turn "`sense 1`" on for all of these devices. Keep these devices selected, without clicking elsewhere. They all begin to move right (in the positive direction of the x-axis). Note that the other points do not recognize them and move away from them, because we have used an `if` and the `disperse` function only effects devices without "`sense 1`".

Try coming back later and using `mux` *instead to see what happens.*

When these devices are completely in the midst of the other points, turn "`sense 1`" off (if you did not click somewhere else, these points should still be selected). The devices around them suddenly disperse away from them again.

Close this program, and then re-execute it. Turn "`sense 1`" on a few points, and then press "m" on your keyboard. All the devices are still there, but they have stopped moving. The "m" key toggles movement on and off from inside the terminal, and as you saw in our terminal statement, the "`-m`" argument there enables movement initially. Press "m" again to turn movement back on, and then press "w."

All the devices that have no doubt strayed outside of their original placement area now return to fit in the original screen size. This argument is very useful because it creates invisible "walls" to push the devices back in to their original distribution area. You can make sure the walls are there from the start by adding a "`-w`" to the command line.

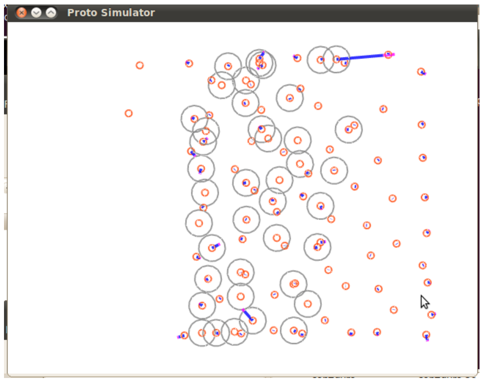


Figure 13: Moving devices dispersing.

Execute this program again (remember, you can simply press the up key in your terminal to use previous statements). When the simulator opens, press the "v" key. The "v" key toggles on and off the display of tuple vectors. You should now see little blue and pink tabs on the devices, pointing in the direction of the vectors returned to the devices. The larger the magnitude of the vectors the longer their tuple displays are. To establish this from the terminal, use the argument "`-sv`".

Let's try a program that uses both space and motion. Take a look at this piece of code:

```
(def MoveIn (src)
  (let ((d (distance-to src)))
    (mux src
         (tup 0 0)
         (let* ((min-d (min-hood+ (nbr d)))
                (vec (int-hood (if (and (< min-d (inf)) (= min-d (nbr d)))
                                   (nbr-vec)
                                   (tup 0 0)))))
           (if (> (vlen vec) 0)
               (norm 0.5 vec)
               (tup 0 0))))))
```

This code is telling all non-source devices to move in towards the nearest source device. Well literally, it tells all the neighbors to move towards whichever of their neighbors is nearest to the source. Because the source remains stationary, the group is eventually pulled to congregate on it. The new parts:

- `let*`: this acts the same way as a normal `let`, except that adding the `*` allows each value to be assigned sequentially, so that, values assigned can use variables assigned before them in the `let*` statement. In this case, `vec` uses `min-d` in its definition.
- `nbr-vec`: this function returns the field of vectors (x, y, z coordinates) to all neighbors within communication distance.
- `int-hood`: takes the integral of the field it is given.

- `norm`: this function tells the device to ignore the magnitude of the vector in its second argument (in this case, the vectors integrated together in `vec`), and just keep the direction given, while resetting this magnitude to the first value in the `norm` function.
- `vlen`: gives the length of a vector.

This `MoveIn` program is really less complicated than it looks. First, like in many of our other programs, it finds each device's distance to the source and names it `d`. Then it asks if any of the devices are sources. When one meets this condition, it is told to remain stationary (but with a `mux` so it can still tell others about its low `d` value), while the rest of the points perform the remaining expressions in the function. The points then find the minimum value of `d` amongst their neighbors. In this case, unlike with `closest` back in Section 6, we're not looking for the lowest `d` anywhere, just amongst our neighbors.

Then, `let*` defines the variable `vec`, which will tell each device which direction it should move towards. This definition takes the integral, approximated by adding up the vectors from each neighbor and weighting each by the amount of nearby space that is nearer to that device than any other. Inside the integral, the `if` asks each neighbor, "is your `min-d` less than infinity?" (this is the same trick from before, asking if there is indeed a closest point) and the second part asks each neighbor whether that neighbor has the lowest `d` value (which vector(s) in the field returned by `(nbr d)` equals `min-d`). If devices nearby meet these qualifications, `nbr-vec` takes the vectors to these neighbors, setting others to zero so that they will not affect the value of the integral. Taking the integral (`int-hood`) of the selected `nbr-vec` value(s) then assigns `vec` as the vector from each device to the devices with the lowest `d` value, which must lie on the shortest path toward a source device.

After all that, the actual code doesn't really seem like much at all. The `if` asks "Is the length of your vector greater than 0?" In other words "have you got a destination that you haven't yet reached?" If this is true, and the point still has some way to go, the device takes the vector it was given, and uses the `norm` function to take away any magnitudes it was given in measuring the vector, and simply assign the set speed (`0.5 meters/second`) in the direction given in the vector. If the `if` does not return true, the device is told to stop with `(tup 0 0)`. Ultimately, this function returns a tuple back to each device, the direction and speed at which it is to move.

Here is the terminal call:

```
proto -m -r 30 "(mov (MoveIn (sense 1)))" -s 0.1
```

Obviously, because it was only given a tuple by this full function our terminal code must tell the devices to move at that velocity using the `mov` function. This is a common way to do movement in Proto: calculate the motions for all the devices as vectors, then only at the very end on the command line send those to `mov`. This makes it easy to combine movement programs together, since a program can pick and choose and blend vectors, but commands to `mov` don't blend—only the last one is taken.

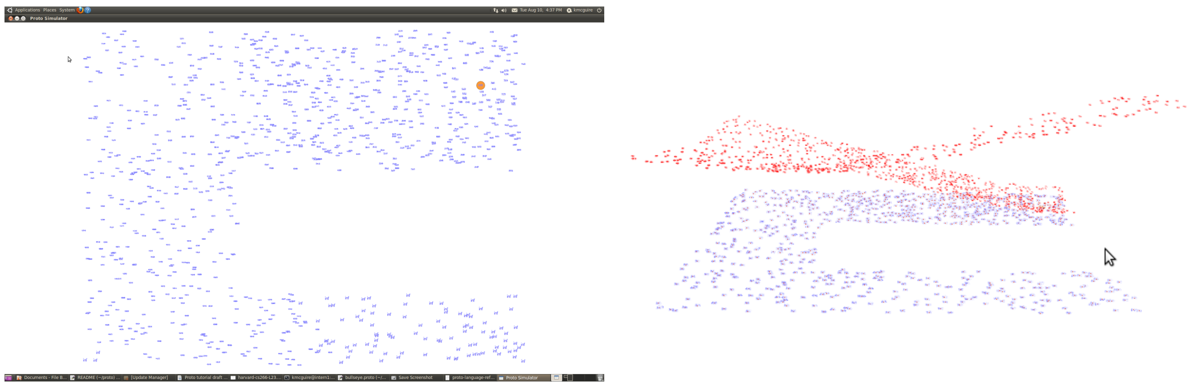
We set our source as any point with "`sense 1`" on, and then execute the function. What about these arguments? Well, these arguments tell the simulator to "`-m`" (enable movement) and "`-r 30`" (increase communication range to ensure most points are incorporated). The "`-s 0.1`" tells the simulator that instead of the default 0.01 simulated seconds per step, we want to run steps of 0.1 simulated seconds. This speeds up the program (since it redraws the image ten times less frequently), instead of speeding up the actual device movement. Having these devices move too quickly may cause the group to tear apart.

Can you figure out how you would speed them up to find out? How fast can you make them go before the program stops working correctly?

Now execute this program. One hundred red circles appear, randomly distributed through the simulator space. Notice they will not move until a source device is designated. Pick any device, and turn "`sense 1`" on. Instantly all the devices begin moving towards each other, running into each other and moving towards the source device. Before 200 simulated seconds are up, the devices have been reduced to a wavering red mass inside the orange circle of your "`sense 1`" device.

Let's think about Proto's movement in a new way. A ship wishes to sail to its destination. All we need to do is create a program so a selected "`sense 1`" point (the ship) moves towards a selected stationary "`sense 2`" point (the destination). That sounds fairly simple, right? Just have the ship find out how far and which way to go, and set it loose. But this actually leads us to a much more challenging way of thinking, in which we will separate the movement from the decision about how to move. Imagine a field of devices, all of them displaying their distance to the source. Illustrate this with a call in your terminal:

```
proto -r 10 -s 1 "(distance-to (sense 1))" -v -n 1000
```



(a) (b)

Figure 14: A C-shaped "sea" of devices (a) and the distance to the destination through the "sea." (b).

The simulator displays a field full of devices with blue "`inf`" values on top of them. This code directs all devices to give their distance to "`sense 1`" as their displayed values. No "`sense 1`" point has been created as of yet, so all their distances are infinite. Before you turn on "`sense 1`", select a large amount of the devices in the middle of the right side. Now move all these points upward (move with shift-right-click-drag) so that the whole display looks like a giant "C" (a C-shaped sea for sailing). Now turn "`sense 1`" on at one of the devices at the end of the upper wing of the "C." All the devices begin to change their values, to reflect their new distances to the source. Notice, however, that the devices' distance values at the end of the lower wing of the "c" are much larger than those in the bottom-left corner. Because all these points determine their distances based on the distance values of their neighbors, these points get their distances by communicating with their neighbors *around* the gap in the "C," rather than over it. Their distance values are greater because communication is limited by their shape. Similar to this, no ocean is perfectly square, so the ship must follow the shape of the ocean. Proto allows this easily, because its values and functions adjust themselves based on the shape of this "ocean."

Now try to visualize this. Imagine that all the distance values become heights above the points on the "C." The "C" would become a road-like spiral going downhill, sloping the whole map towards the source.

In fact, why don't we visualize this in the Proto simulator? Change the command line as follows:

```
proto -r 10 -s 1 "(red (* 0.3 (distance-to (sense 1))))" -l -v -n 1000
```

This is the same as before, but turns on LEDs with "`-l`" and feeds the distance values to the red LED after scaling them down so they'll fit on the screen better. Make your "C" sea as before and turn on "`sense 1`" on an upper right device. If you rotate the display around (left-drag with the mouse), you should see something like in Figure 14(b). Remember, you can reset the viewing angle in the display by pressing "z."

Why not use the fact that distances are shaped by the space to our advantage? In creating this ship voyaging program, look at it as if the ship needs to "roll" downhill towards the destination, from greater to lesser distance values. How do we manage this?

All we need is to have the ship ask the devices within its neighborhood if their distance values are less than its own. It can integrate the vectors to all devices in which this is true, which averages their directions, but not their magnitudes, and make this its direction. This makes it a far more compact program, and we do not have to worry about communication range because the ship only has to take into account those devices in its direct neighborhood. This also makes it possible for our program to work in more realistic environments, where we don't have a perfectly square ocean.

Try building this program on your own. Here are some guidelines:

- Have each device establish its own distance to the destination. You will probably want to name this value with a `let`.
- Ask the ship to travel towards the integral (`int-hood`) of the vectors to neighbors that are closer to the destination than it is. Use the `norm` function for the final speed and direction of the ship.
- Tell the destination and all other points to stay put.

Remember: `mux`s allow for all parts of a program to evaluate and share information, while the `if` only computes the `true` expression in the places where the `test` expression is true, or the `false` expression where the `test` is false. Be careful that where you need your devices to take devices in both branches into account, you use `mux`. Try to differentiate between these when writing your program. Refer to the Proto Language Reference if you need help. Consider and refer back to the "MoveIn" program, to best remember how to intertwine space and motion. When you finish, look here for our code:

```
(def voyage (ship destination)
  (let ((d (distance-to destination)))
    (mux destination
         (tup 0 0)
         (mux ship
              (let ((vec (int-hood
                           (if (and (< (nbr d) (inf))
                                    (> d (nbr d)))
                               (nbr-vec)
                               (tup 0 0)))))
                (if (> (vlen vec) 0)
                    (norm 0.2 vec)
                    (tup 0 0)))
              (tup 0 0)))))
```

This program establishes `d` in every device as its individual distance to the source. Then it asks each device whether it is the destination. The destination is instructed not to move with `(tup 0 0)`. We use `mux` here to make sure that the destination will participate in the calculation of which way the ship should go. Then the program asks those devices in the ship (`mux` again for a similar reason) to create a vector (`vec`). This "`vec`" is the integral of the field of vectors to neighbors that meet these conditions: their distances to the source are less than infinity (to ensure that a destination has been established), and the ship's distance to the source is greater than theirs. This way, the ship now has the vector of the general direction of all the devices in its neighborhood whose values of `d` are less (closer to the source). Proto continuously asks if this vector length (`vlen`) is greater than zero (this ship still has some distance to travel), and if it is, the ship should continue forward at 0.2 meters per second speed, and in the direction of the vector it has established.

Call this code in your terminal:

```
proto -m -n 1000 -s 1 "(mov (voyage (sense 1) (sense 2)))"
```

This code uses a field with 1000 devices, simulating a large ocean. Again, we speed up virtual seconds, this time even faster, so that the steps run much quicker, but the ship does not have to increase its speed. The "`-m`", as expected, allows movement.

Execute this code. A large field appears full of red circles representing devices. Turn "`sense 1`" on one point, and "`sense 2`" on another. Wait a few seconds while the information is flowing. When neighbor-to-neighbor communication flowing through the field of devices informs the "`sense 1`" point that there is a destination, it begins moving through the ocean of devices in a semi-straight line towards the destination. Within a minute or so, it reaches and hovers above the destination device.

Close the program, and re-execute it from your terminal. This time, before turning any "`sense`" on, try to create the same gap we created earlier in this section. If we put the two "`sense`" points each on the ends of separate wings of the "C" shape, you will notice that the ship device goes all the way around the "C" (through the ocean) to reach its destination, rather than going across the gap. With Proto, the programmer is quite able to adapt a program to the limitations it might have in real life, such as a ship limited by the shape of its ocean. Warp the shape of the ocean even more and retry the program, and watch it navigate any channel as a real ship would.

If you are this far, you now have a fairly good grasp on the movement aspect of Proto, as well as the space and time branches covered earlier. You can probably see how diverse uses for Proto can be, as it can be applied in numerous real-life situations. Remember if you were stumped by this program, or even if you feel like you simply want a better grasp on any of these functions, they are all defined in the Proto Language Reference. Movement, space, and time combine to give Proto the ability to perform advanced spatial computing tasks. We will explore these abilities more in the next section.

Exercises

Exercise 1: Adapt the `closest` *program from Section 6, so that the closest point moves to the source.*

Exercise 2: Adapt the `emergency` *program so that the police device moves to the site of the emergency.*

Exercise 3: Create a program in which regular points move left, "`sense 1`*" points move right, "*`sense 2`*" points move up, and "*`sense 3`*" points move down.*

10 Advanced Proto

Now that we have covered the three main aspects, Proto can be taken to higher levels than so far explained in the tutorial. We will look at two complex programs, for flocking and target tracking, then do a "graduation test" problem.

Flocking Go to the demos folder inside the Proto directory. Open "`flock.proto`". This looks like a big program, but all the text down at the bottom, where the lines begin with "`;;`" are simply comments letting the reader know about this program. It is a good idea to use these comments in your own programs to remind yourself and others what the objective of the program is. Also, the programmer has left a terminal call code (the second comment down), so that one can easily run this code without having to remember the preferred way to call it.

What are `flock.proto`'s objectives? It wants all the devices to arbitrarily group together into flocks of devices following their neighbors. Any "`sense 1`" devices should travel towards the middle of the screen, pulling the devices in their groups along with them. It becomes a battle between "`sense 1`" and non-"`sense 1`" devices to move towards the middle of the screen or ignore the middle (hence usually moving away). When there are more than a few "`sense 1`" devices, they will usually win, but sometimes the flock will tear apart into more than one group.

`flock.proto` uses a few new functions:

- `normalize`: this acts in a similar way to the `norm` function, which we learned earlier, but instead of taking both a value and a vector, and setting the length to that of the given value, the `normalize` function just takes the vector and sets the length to one. Both functions allow the direction of the given vector to remain unchanged.

- `vdot`: this operator takes the dot product of the two vectors given after it. The dot product is an algebraic operation that takes two coordinate vectors and returns a single number obtained by multiplying corresponding entries and adding up those products. For example, two vectors of values [1 0 4] and [3 7 2] have a dot product of $(1*3+0*7+4*2) = 11$.
- `rep`: This is not new, but we have not used it since the beginning of Section 8. You are reminded to look it up in the Proto Language Reference to remind yourself of the basic form of a `rep` expression.

Although these are the only totally new parts, you will find that many of the things here are used in very different ways than previous methods. Let's run through exactly how this function executes. Looking at the code:

```
(def flock (dir)
  (rep v
   (tup 0 0 0)
   (let ((d
          (normalize
           (int-hood
            (if (< (nbr-range) 5)
                (* -1 (normalize (nbr-vec)))
                (if (> (nbr-range) 10)
                    (* 0.2 (normalize (nbr-vec)))
                    (normalize (nbr v))))))))
     (normalize
      (+ dir (mux (> (vdot d d) 0) d v))))))
```

Before we can really run through this code, we must also know what the single argument "`dir`" holds as its value. As shown in the terminal call code, `flock` is called with its `dir` as this: `(* -0.5 (sense 1) (normalize (coord)))`. If you look up the "`coord`" part of this, it is not defined in the Proto Language Reference! That's because it gives each device a vector of its global coordinates. We don't want to assume that is always possible, so `coord` is in one of the optional parts of the simulator model—see the Proto Simulator User Manual.

Imagine a coordinate field. The middle of the screen is coordinates $(0, 0)$. A `sense 1` device could be in any of the four quadrants, at any set of coordinates. The "`(normalize coord)`" part of this statement establishes those coordinates as a direction to travel. If a device is at (x, y) on the coordinate plane, what do we need to do to get it to the origin? We need to have it travel $(-x, -y)$. By multiplying the coordinates of the device by `-0.5`, we tell the device to travel in the opposite direction of its own coordinates, thereby traveling back to the origin at our newly set speed of 0.5 meters/second. Finally, multiplying by `(sense 1)` means that only "`sense 1`" devices will move this way: their value from "`(sense 1)`" is 1, while others get 0, which will turn the whole vector to $(0, 0)$ so they aren't trying to go anywhere in particular.

This is a primary part of our program. We have already established which way "`sense 1`" devices want to go. We feed this into `flock` as an argument, and then continue with the program. The `flock` program uses the `rep` function to evolve the variable `v`. This `v` is a vector initialized to 0 (stopped), and then evolved by the remainder of the function. We create a variable `d` which establishes the direction in which each device wants to travel. The definition adds up influences from each of its neighbors, which fall into three categories. Neighbors less than 5 meters away are "too close" and the device moves at a magnitude of one away (negative direction) from those. Neighbors that are more than 10 meters away are "too far" and the device moves at a magnitude of 0.2 toward them. The device tries to align with neighbors at a distance between 5 and 10 meters. In this way, devices form groups with their neighbors, while still keeping a certain distance away.

In the actual function part inside the `let`, devices are given a final direction of `dir` (which only matters for sense 1 devices) plus their values of `d`, unless the dot product of `d` was zero (another way of calculating vector length), which generally means there are no neighbors nearby, so just use the same `v` as before.

In the end:

- Regular points: move away from close neighbors, and towards far ones. Try to move with the direction of the group.
- Sense 1 points: move towards the middle at strength "dir," unless the pull of the `d` value (the pull from other points), is greater.

Try executing this program with the call code given in the file. Remember, when you execute this, we are no longer in your "MyPrograms" directory. You will have to switch to the "Demos" directory of the Proto distribution to access this program and call it from the terminal. Immediately you see a field of purple devices contorting and moving into clusters. Now press "m" to halt movement. The purple was caused by all the blue/red vectors that are displayed. Select a large piece of one of the clusters and turn "`sense 1`" on. Notice that some of the nearby blue devices seem to blink and adjust their vector display slightly.

Now turn movement back on. At first it may seem that the groups are simply continuing to contort, but you will see, if you selected a large group, the "`sense 1`" points tug away from the group, probably taking a good fraction of the regular points with them, to "flock" in the middle of the screen. The other groups simply continue on their way. Try to fool with this program. Execute it a few more times, seeing how "`sense 1`" points behave when they are only a small part of the group. See how a regular point behaves when it is out of the communication range of all other points. This program is designed with the principles of Iain Couzin's 2005 paper on flock leadership, called "Effective leadership and decision-making in animal groups on the move," in the journal "Nature."

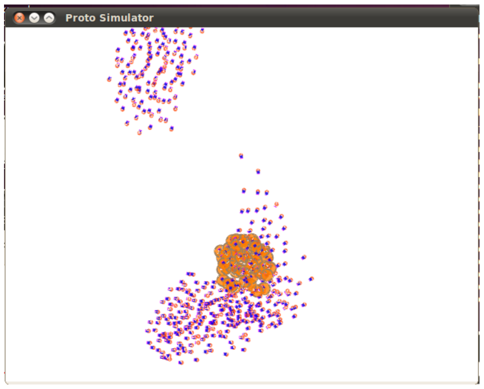


Figure 15: Flocking devices

Target Tracking Open the "`proto/demos`" folder again. Find `track-demo.proto` and open it up. It may look intimidating, but don't be fooled. You know that all the "`;;`" lines are comments, and if you look carefully, there are actually four functions in here, not simply one. This is because the main function we will look at, `track-demo`, calls all the other functions in this file at some point, directly in itself, or indirectly through another function. We do not even have to worry about the first function defined, "`broadcast`", because we already know what the `broadcast` function does. So scroll down until you see the line beginning with "`(def channel`"; we will start there.

The function `channel`'s purpose is to establish a fat line of devices between the source and the destination devices. It returns true for all the points that make up this channel, and false for all the rest. Realize that because `track-demo` does not take any arguments, all the functions that it calls (including `channel`) must get their arguments from inside it. Because `channel` is actually called in `track`, which is itself called by `track-demo`, we must follow first the arguments given to `track` in `track-demo`, and then what arguments these create in `channel`. If we define all the arguments used in all functions:

- `target` in `track` is any "`sense 1`" device
- `dst` in `track` is any "`sense 2`" device
- `coord` in `track` is the coordinates of devices
- `src` in `channel` is any `sense 1` device
- `dst` in `channel` is any "`sense 2`" device

- `width` in `channel` is 10

Okay, so `channel` establishes `d` as the distance between the source and the destination. Then it establishes `trail` as a boolean (true or false) variable where each device asks: Is my distance to the source plus my distance to the destination, less than or equal to their distance between each other plus one meter? If this is true, they are on the shortest path between the source and the destination. If our distance numbers were perfectly accurate, we wouldn't have the "plus one," but they aren't, and the extra bit makes sure we get a trail.

Finally, `channel` returns true for all devices in which `d` is less than infinity (ensuring that a destination and a source have been established), and which fit the dilated `width` of the trail. This `dilate` function simply takes the given devices—in this case our shortest-path `trail`—and expands it to include any devices that are within the given `width`. The `width` given to this call of `dilate` is ten, so any devices ten meters or less from the `trail` become part of the channel.

Now switch to the `track` function. This takes all its arguments from the list above as well. Remember that the `all` function simply runs through all the expressions it is given in parallel. The function still returns the value of the last expression that it is given. First, `track` restricts to run on only the points returned as true from the `channel` function. Then these devices turn their LEDs blue, and the `dst` device computes the distance between its own coordinates and the coordinates of the `target`, which are `broadcast` to it through the channel (remember that the `broadcast` is running only inside the channel because we are using `if`). The other points simply return (tup 0 0 0).

Lastly, the `track-demo` function. This uses the `all` function again, and also two other functions:

- `rnd`: this is simply a function that chooses a random number between the two numbers that follow it. In this case, it picks a random number between 0 and 1.
- `once`: recall from Section 7 that this computes the expression after it only once and then remembers it.

This function first establishes the true or false boolean variable "`mobile`", which has a 50/50 chance of being true, and stays that way because of the "`once`". Then the next statement tells the devices to move if they are a "`sense 1`" devices or a "`sense 2`" device, or if `mobile` is true (approximately half of the devices). Then they move at 0.01 magnitude of the vectors returned by the "`dither`" function, which results in slow movement in a random direction. Finally, also perform the track function. Note that the track function simply returns a tuple to the target at the destination, which is displayed but causes no motion.

Execute this program with the last terminal code listed in the `track-demo.proto` file. Again, remember that you will need to be in the `proto/demos` directory in your terminal to execute this. Turn on "`sense 1`" on one point, and "`sense 2`" on another. You will see blue dots fan out from the target and destination, then link up and suddenly a vector display forms linking the two. Half the points will float around (dither), including these two, but they will remain connected by this tuple display.

Graduation Test Okay, now you are probably pretty handy at Proto, so let's try one last programming test. This one uses time, space and movement together. Here is the situation:

There is an Olympic runner, who is up for the race of her lifetime. The lowest time of the day is on the board. If she can beat it, she wins the gold medal. Build a function that takes several arguments (speed, time, runner, start, and finish) to help you simulate how fast she will need to go. Execute this program with the runner as "`sense 1`", the start line as "`sense 2`", and the finish line as "`sense 3`". When ready to execute, input the best time currently on the boards (you may choose this). When executing the program, you will want "`sense 1`" to approach the starting line, and then stop. When the finish line is turned on, have both the timer start and the runner begin running. If the runner reaches the finish line before the timer is up, turn on a green LED on the runner. If she does not reach it in time, stop him, and turn on a red LED instead. Adjust the runner's speed and the distance between the start and finish until you have the runner win a narrow victory.

Hint: the `letfed` and `broadcast` functions will prove helpful in this program. Look them up in the Proto Language Reference for help. Also, look at your previous "ship voyage" program. Using this may simplify the movement part of your program significantly. When you think you have it, look here for our code:

```
(def olympian (speed time runner start finish)
  (letfed ((t 0 (if finish (+ t (dt)) 0)))
    (if (= (broadcast finish t) 0)
        (mov (goto speed runner start))
        (if (< (broadcast finish t) time)
            (let ((d (distance-to finish)))
              (if (and runner (< d 1))
                  (mov (tup 0 0 0))
                  (mov (goto speed runner finish))))
            (tup 0 0 0)))
    ; first 'paragraph' deals with motion vectors

    (let ((d (distance-to finish)))
      (if (and runner (< d 1))
          (green 1)
          (if (< (broadcast finish t) time)
              0
              (if runner (red 1) 0))))
    ; second 'paragraph' deals with LEDs
    ))
```

Now, our code actually uses a sub-functions for this project, as you will see if you look closely and find the `goto` function that is hidden in there. This is not a function we have simply not covered, but a function we wrote specifically for use in this program. A large part of our `olympian` function was simply moving one point to another (runner to start and runner to finish), so we pulled this out as a separate new `goto` function, and then called it inside of the `olympian` function instead of putting all of its code there twice. Here is our `goto` function.

```
(def goto (speed mover destination)
 (let ((d (distance-to destination)))
   (mux destination
        (tup 0 0 0)
        (mux mover
             (let* ((vec (int-hood
                           (if (and (< (nbr d) (inf))
                                    (> d (nbr d)))
                               (nbr-vec)
                               (tup 0 0 0)))))
               (if (> (vlen vec) 0)
                   (norm speed vec)
                   (tup 0 0 0)))
             (tup 0 0 0)))))
```

Looking over this, you may notice that it is almost entirely identical to the `voyage` function that we created in the Section 9 of this tutorial. The only differences, in fact, are that we added a speed argument so that we may choose the speed of motion when we call the function, and changed the "`ship`" variable name to a more generic "`mover`". By using this `goto` function, as with the `voyage` program, the runner will follow an indirect path to the finish line. The user of this program can now set an actual track down for the runner to follow to the finish line, rather than simply cutting through on a straight line to the finish line.

Knowing this `goto` function, let's look at the `olympian` program and figure out how it works. It begins by starting a `letfed` timer, which evolves only inside the finish line device. Remember, the `letfed` timer works much like the `rep` timer, but instead of just returning the variable `t`, it makes it available for use by the rest of the program. In this case, we establish this `t` to always be zero except in the finish line device.

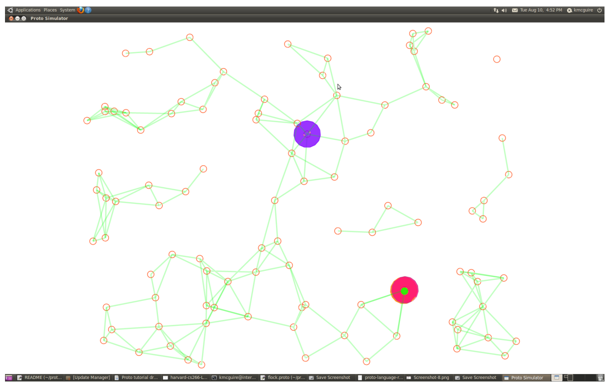
Next we see what looks like two separate "paragraphs" of code, with spaces in between. Both of these pieces of code are actually running at once. These parts cannot easily be combined into one block of nested `if`s, because they return different data types. The first part deals with movement and therefore tuple data types, and the second deals with LEDs, which return scalar (real number) values.

The first part asks whether the value of `t` being broadcast from the finish device is zero (there is not yet a finish line, so the race has not begun). If it is zero, then have the runner "`goto`" the start. Remember that the `goto` function returns a vector, so we must tell the device to move at that velocity with the `mov` function. If this value of `t` broadcast from the finish is not zero (the race has begun), we want the runner to `goto` the finish line, but only if she has not yet reached the finish line, and if the timer has not yet exceeded the lowest time, which we input into the function as "`time`". The `if` statement here checks whether the timer has yet exceeded the time, and if it has the runner needs to stop. If it hasn't, the next `if` checks whether or not the runner is within one meter from the finish line (essentially there), and if the runner is, it is again told to stop. If you used a zero value there, it is highly unlikely that the runner will ever reach exactly zero, and it will more likely waver over the finish line indefinitely. Otherwise, the runner continues to go towards the finish line until one or the other of these checks become true.

The second part is relatively simple. We simply ask again those same two questions: "Have I reached the finish line?" and "If not, has the timer exceeded the input value of time?." If the first question is true, turn the LED green, otherwise if the second question is true, turn the LED red. In all other cases, keep the LED off. Try running `olympian` with this call in your terminal:

```
proto -m -s 1 -l -c "(olympian 0.2 500 (sense 1) (sense 2) (sense 3))"
```

Before you execute this, look at some of the values we have put in as the variables. We have set our speed to 0.2 meters/second, and also sped up the simulation step size with the "`-s 1`" command. We have set the time of the fastest runner on the board so far as 500 simulated seconds, and enabled movement, LEDs and visible network connections. The runner, start line, and finish line have been set to their respective senses.


(a)

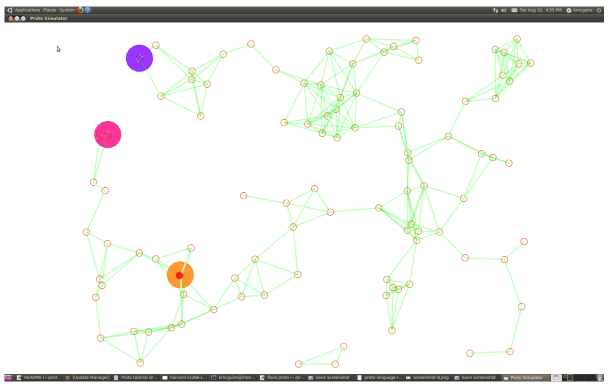

(b)

Figure 16: The `olympian` wins (a) and loses (b) a race.

Execute this call in the terminal. You should see an interestingly structured web of green connections and little red circles. You may either simply take the large and messy route in front of you as the runner's "track," or create one yourself by moving around the points. Make sure the track that you want to use is all connected. Pick any point connected to the track (which will not break any major connections by moving), and set it as the runner ("`sense 1`"). Then set a point as the start line ("`sense 2`"), and watch as the runner makes its way over to the start. When the runner has reached the start line, set a finish line to kick off the race. If they are connected, the runner will soon begin to make its way to the finish, at the set speed of 0.2 meters/second. Depending on how far away your start and finish lines are, the runner will either stop and turn its LED red, or go all the way to the finish line and turn its LED green, winning the race.

Re-execute this program, and change the inputs for speed and time in your terminal. Change the distance and the "track" in the simulator. See how this effects the outcome of the race. Try the race with only ten devices and set up a small, clearly formed track for the runner to follow.

Now, let me give you a new idea. In this program, and the demo ones that we looked at, you may have wondered why the tup values had three 0's rather than just two. Proto, along with the many other things it can do, can take its simulation to the literal next dimension. These zeros become the x, y and z coordinates of a 3D coordinate plane. Try the same `olympian` program call, adding a "`-3d`" argument to the terminal call code. Also, extend the range to 40, and get rid of the "`-c`" argument to stop the connection display. Execute this.

You should now see the regular field of 100 devices, but this time the little circles are spheres instead, and are all different sizes. This is because some of them are farther away than others. Left-click-drag to rotate the field of view and see the box-like collection of devices from other angles. If you turn the senses on as you would normally in this program, the runner will actually run at different heights within the box to get to a finish line on a totally different plane.

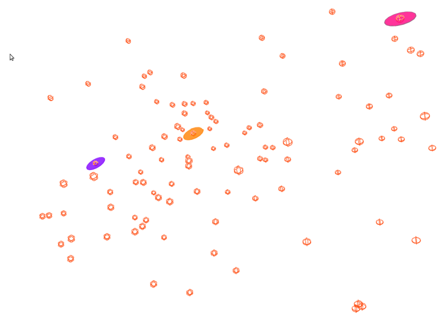


Figure 17: The `olympian` runs a 3D race.

Challenge: Go back to the MoveIn program, and make it run in 3d mode.

Exercises

Exercise 1: Go back to the examples and programs you struggled with. Try them again with your new understanding.

Exercise 2: Right now the `flock` *program tells the Proto simulator to change the flocks movement based on three even sections of the default communication range of fifteen meters (within 5 meters, above 10 meters, and in between). Adjust this so it takes three even sections of any given communication range.*

Exercise 3: Adjust the `olympian` *program so that the finish and start lines are established as actual lines (between two points), and so that multiple runners can run, one after another. (Multiple runners can run currently, but after a finish line has been established they no longer take the start line into account).*

Exercise 4: Change the `olympian` *program so that it detects when a runner has* crossed *the finish line rather than when a runner has reached it.*

Exercise 5: Create a 3D "pool" in which someone is diving for treasure. Have one device at the top of the ocean dive for a stationary device at the bottom, and then have the diver bring the "treasure" back to the top with it. Set a timer to make sure the diver doesn't run out of air, and light an LED when it is close to running out.

Exercise 6: Imagine some other real-life situation (some ideas: bowling, animals foraging for food, someone parting a crowd as he walks). Apply Proto to model it.

If you have made it to this point, and you are pretty confident in the programs you have read and built, you have grasped how to think in Proto. Congratulations! We encourage you to take Proto further with some exploits of your own, and remember to use the Proto Language Reference for any of the functions we have not explained in this tutorial. Hopefully you now, like us, also think that Proto is an extremely useful and easy way to program spatial computers.