Introduction to DML

Straightforward specification of protocols for digital microfluidics boards

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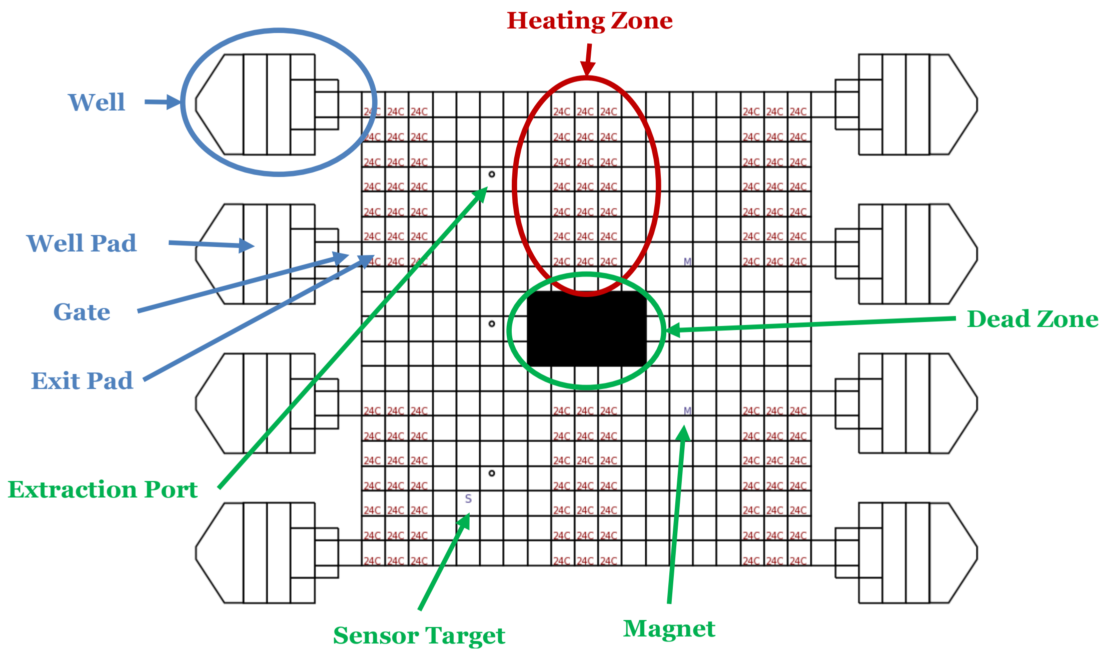
CHAPTER ONE: **Introduction**

DMF, short for "Digital Microfluidics Language" is a language specifically designed for describing experiments and protocols to be run a digital microfluidics boards.

Digital Microfluidics Context



Guiding Principles

There are a number of principles that I kept in mind when designing DML. Some of these principles occasionally conflicted with one another, forcing me to make tradeoffs, but on the whole, they reinforced one another.

A warning to the reader, though. Most of these principles are designed to make the language *unsurprising*, but unsurprising is not necessarily *simple*, and it certainly isn't always simple to describe. When I go into detail below about how the language actually works, you may find your eyes glazing over. That's okay. In most cases—if I did my job right—you should be able to look at the examples and say "Yeah, that makes sense."

The customer is not a programmer

This principle can also be stated as "I am not the client," and it can be a hard one to internalize. I wrote my first program in 1978, drew my first paycheck as a programmer in 1980, and designed my first programming language in about 1985. Programming makes sense to me at a level that it doesn't to most people, even most computer scientists.

But when designing a language for other people to use, that doesn't matter. What matters is that it is easy to use for the people who will use it. In this case, that means scientists and engineers, especially those who need to use digital microfluidics boards, and these people cannot be expected to have more than a very basic exposure to writing their own programs in a traditional programming language like C++, Java, or even Python. But they do know what they would like their programs to do, and making the transition from their desired behavior to (correct) DML code simple is the ultimate goal.

The customer's informal description is the gold standard

In almost all cases, the customer already has a way of informally writing down (or drawing or talking through) a description of what they want their program to do. In a perfect world, that would be enough. The world we live in is far from perfect, but to the extent that we can come closer to that informal description in a program whose behavior mimics what is desired, we have a better language.

If the programmer wants to talk about "well number 1" on their board, it makes little sense to make them write **`board.wells()[1]`**, when you can just let them write **`well #1`**. If they want to transfer in 0.5 µL of a mixture of reagents A and B in a 2:1 ratio, why not let them write **`0.5uL of 2*A+B`**?

Physical quantities are not numbers

Anybody who's known me for any length of time knows that this is one of my biggest pet peeves. Too often, code that deals with real-word quantities like volume, voltage, or even time has them represented as floating point numbers with — if you're very lucky — a comment telling the programmer that this functions parameter should represent a voltage in millivolts, but nothing stops the caller from accidentally passing in a value in volts or from a programmer from misspelling a variable and winding up adding a time in milliseconds to a distance in meters.

Every programmer has screwed up multiple times misremembering whether a **`sleep()`** function takes its number in seconds or milliseconds. Programs have crashed … and so have spacecraft. People have gotten the wrong radiation therapy dose and died.

This was an embarrassment thirty years ago; it's inexcusable today. Physical quantities are very important to scientists and engineers, and it's crucial that DML takes away the ability to make stupid mistakes. It doesn't matter if you said that **`t`** was **`20 seconds`**. It's just a **`time`**, and you can add it to **`3 hours`** or compare it against **`0.5 minutes`** without worry. And you can't add it to a **`voltage`** or ask whether it's less than **`1mL`**. The compiler will catch those errors when the program is compiled.

English is better than Computerese

The programmer's informal description is almost certainly written largely in some form of a natural language, so approximating it will often mean approximating natural language. At this point, we can only go so far, but where we can, we should. Taking English — the modern scientific lingua franca and the language I know best — as a model, this means doing things like allowing multi-word names when possible,[1] so a well can have an associated **`exit direction`** rather than an **`exit_dir`**. It means that when asking for a well's exit direction, instead of saying **`w.exit_dir`**, you can say **`the well's exit direction`**. Often this will mean that a program will contain more characters, but the increase in clarity can more than offset it.

Don't worry about mistakes users won't make

In DML, you can say that a parameter to a function is **`a drop`**. You can also say that it is **`an integer`**. So how much complexity does the compiler have to point out to the programmer that they accidentally said **`an drop`**? Zero. It's an error that an English speaker is unlikely to make, and if they do make it, the default behavior of not distinguishing between the two is highly unlikely to cause problems. So we don't worry about it. This sort of thing comes up all the time as a language gets closer to a natural language. What's important is that you do the right thing with the input you're likely to get and that you don't do something wrong if the user makes a simple

[1] It hasn't been to the extent I'd like, but I'm working on it.

mistake of the sort that users are likely to make. But errors you're unlikely to see aren't worth spending a lot of time worrying about.

The principle of least astonishment

This rule dates back at least to the 1960s. In language design it recognizes that often what a user expects a given bit of syntax to do in one context may well be different from what they expect the same syntax to do in another context, and that in this case, it's far more important that the language just do what they expect in each than that it be consistent and surprise them in one. Similarly, if a strict adherence to simple rules means that code that obviously should do something is considered ill-formed, that's a problem. The language should be changed so that it does what it obviously should, even if that means that a detailed explanation of when it does what may be complex. If the language designer has done their job, the programmer won't ever notice most of the inconsistencies, because they match their expectations.

It's easier to learn a few new things that a lot of them

While the customer may not be a programmer, and while we want to be close to their informal description, it's okay if we introduce notation they're not familiar with, especially when they're being asked to describe things at a lower level than they're used to. But when we do this, it's important that we don't do it too often, so when we do introduce something, we should use it as often as possible, so that it becomes second nature.

In DML, it's common to have a drop go through a sequence of actions. Move it here, merge it with another drop, walk it around a bit, move it over here, split it, enter this well. This isn't the level a protocol designer thinks at, so DML introduces a notion of *injection* (based on Unix shell pipes) in which an object is passed to a function, and the value is passed to another function, and so on. Once the user has gotten used to the weird (though hopefully evocative) **`o : X : Y`** syntax, though, we can exploit the Principle of Least Astonishment to present the user with right-hand-side values that aren't functions, but whose behavior there is what they expect without thinking about it. If **`d`** is a drop, **`d : east`** moves the drop one pad to the east. If **`c`** is some component that can be turned on and off, **`c : off`** turns it off. If we're in the middle of an injection chain moving a drop and we see **`print "We're at", d's pad`**, of course it's going to print that message. If a target is **`wait for 10 seconds`**, that's what we'll do.

There's more than one way to do it

This is one of the guiding principles espoused by Larry Wall in his design of the programming language Perl in the late 1980s, and it ties in with several of the principles described above. Different people will have different ways of describing the same thing, and not only is that okay, but to the extent possible, you should support many of them.

In DML, a heater has a `current temperature` attribute. Or, if the user prefers, it can be `temperature` or `temp` or `current temp`. You can describe a variable's type as `(eventual) drop` or `eventual drop` or `an (eventual) drop` or `an eventual drop`. You can `repeat until` a condition is true, and you can `repeat while` its opposite is true. You can introduce a function definition with `define` or `def` or `macro` or, depending on the definition, `function, func`, `procedure`, `proc`, or `action`. There are omittable "noise words" all over the place. You can `pause the clock` or simply `pause clock`. You can refer to the same direction as `up` or `north`, and you rotate a direction `right` or `clockwise`. You can ask whether `the pad has a drop` or `doesn't have a drop` or whether `the pad's drop exists` or `is not missing` or …

When coupled with the principle of least astonishment, this can mean that whatever the programmer tries is (hopefully) likely to do what they want. And if it doesn't, it should in a later version.

Easy things should be easy, and hard things should be possible

This is Larry Wall's other dictum for Perl. In the design of DML, I've focused more on the first part, trying to prioritize things so that the things that programmers are going to need to do most of the time should be simple to do, and that it's okay if the rest is ugly or cumbersome. Indeed it can sometimes be beneficial to say "This thing is dangerous, though sometimes necessary, and I'm going to implement it in such a way that you know you're doing something dangerous". (Of course, the next step is sitting back and figuring out *why* the user wants to do that and seeing whether there isn't a way to support that directly at a higher (and safer) level.)

Where DML falls short at the moment is the second half of the slogan. There are a lot of things that I can see users wanting to do with the language that it simply doesn't support yet. This is largely due to lack of time, and hopefully it will improve.

This isn't the last version of the language

All languages evolve over time. It's okay if this version of the language doesn't do everything that I want it to. The next version will be better. The syntax will be cleaner and less surprising. It will allow programmers to more simply write things that are hard today and to write things that are simply impossible today. The compiler will be more efficient, and the code will run faster.

A corollary of this, however, is that as soon as people start writing programs in a language, it becomes more difficult to make changes that will break their code, so you have to start worrying about backwards compatibility.

This, however, should not be overstated, especially at such an early stage of language design. When I was in college, I took a class in programming language design from Al Aho of Bell Labs. He recounted an anecdote about the development of the **make** utility in 1976, about a decade earlier, and in particular, the syntax of the files that drove it. According to him, Stuart Feldman threw together a little tool for a project he was working on, and other programmers there soon started using it. He realized that the syntax of the files was terrible, but it did the job for what he needed, and he was a busy man. By the time he had a chance to revisit the design some months later, he decided that it was too late to change it: *dozens* of people were using it. And a decade later, tens of thousands of us (at least) were struggling daily with the same awful syntax.

Trade complexity below for simplicity above

In may systems there's a tradeoff between the complexity of the interface presented to the user and the complexity of the system that implements the interface. In almost all cases, it's worth making the invisible implementation more complex in order to make the user-visible portions simple to use.

Rough Spots and Missing Pieces

While I'm happy with a lot of DML and its implementation, there is still a fair bit that I'm not happy with. In no particular order:

- The error messages from the compiler are *really* bad. Most of this has to do with the ANTLR4 tool used to do the parsing, but some of it is due to my not having come up with a coherent method of reporting errors from within the compiler proper. Code that compiles without error is fine, but if there's a syntax error, it can be *very* difficult for the user to identify where the problem is.[2] It is apparently possible for ANTLR4 parsers to provide better error messages with support from the compiler-writer (i.e., me), but I haven't had the chance to put much effort into this.

- It's unconscionable that there isn't yet support for things like sequences or mappings and that there's no way for users to define their own classes, attributes, and types (especially enumerated types).
- The syntax could (and should) be a lot more natural-language-like. My intention was to make things to that all names could have spaces in them and that there would be notions of things like adjectives and prepositions. There are lots of cases where parentheses are still required where they shouldn't be. (For example, you have to say **`w : require(2uL of A)`**, where you should simply be able to say **`w : require 2uL of A`**.) There are good reasons why I wasn't able to get around them, but they should go away in the future.
- In particular, it would be very nice to have the ability to use "it" to refer to whatever it is we were just acting on. This would allow for a more verbose but clearer way of doing what we currently do with injection chains.
- I don't like forcing non-programmers to use braces for blocks. In my initial PhysL design ideas, blocks were done with bullets and indentation, but it wasn't clear that that would be (1) easily parsable with ANTLR4 and (2) easily typable by the user. This should be revisited.
- There really should be a clearer alternative to the current double-bracket parallel block notation.
- It's currently impossible to write overloaded functions, and the lack of this ability makes lots of other things uglier in both the implementation and in user-visible portions. (For example, there's a mechanism in there to support built-in overloaded functions, because they're actually necessary, but they complicate things a great deal.) I have a partial implementation of this, but I couldn't get it to work in time.
- There are a lot of places where the underlying Thylacine implementation bleeds through to the user in ways that they should be insulated from.

[2] As a clue, if you see an error message that starts with something like **`45:12`**, look at line 45, character 12. But if there are multiple such errors, the real problem will often be on the second or third of them. In any case, the actual message is probably not going to give you a lot of guidance. You're probably better off just looking at the line in question and seeing if you can figure out what might be wrong.

- Interaction with the user is very primitive. The program can `prompt` the user, putting up a dialog box, but this is essentially just a pause. There's no way for the user to provide input that could guide the program.
- There's no way to read or write files or communicate with remote sites.
- For Python-level Thylacine protocols, it was typically necessary to use things like barriers to do more sophisticated traffic control to prevent drops from deadlocking. This should be extended to DML.
- Similarly, Thylacine has a notion of multi-drop mixing and dilution that needs to be exposed in DML in as simple a way as 2-drop merging and mixing.
- Ideally, the language should take care of motion planning in `to pad` expressions so that the user doesn't have to worry about avoiding dead pads and deadlocking with other drops. This may imply changes to the underlying Thylacine system in which drops actually know their targets so that the system can detect deadlock and figure out how to back out of it.
- DML currently can only talk about drops that sit on single pads on the board. The underlying Thylacine system is able to model *blobs* of liquid that may be more than a single drop in size. These should be supported directly in DML.
- It should be possible to do a lot more at a higher level. There's no reason why the programmer can't talk about high-level desires (mix this reagent with that one, heat it for this long at that temperature) and have the compiler figure out what to dispense from where and which heater to use. But that may be a higher-level language that compiles down to DML.
- There's currently no way to write a parameter declaration for parameters that take functions. You can do it for variables by using `local`, but you can't actually specify. Similarly, you can't specify the return type for a function that returns a function.
- There needs to be a way to import one file from another (and from the interpreter), with a check to make sure that it isn't imported twice and we don't have a cycle.

CHAPTER TWO: A Tutorial Example

In this chapter, we'll look at a worked example. Note that this is not necessarily a *realistic* example, but it demonstrates many of the features of a language that a user is likely to need.

In this example, we'll demonstrate dispensing drops, moving them around simultaneously on the board, merging them together and splitting them apart, heating them, using a sensor to take measurements on them, making decisions based on the measurements, and finally, moving drops into wells or extracting them via (manual or robotic) pipetting through an extraction port.

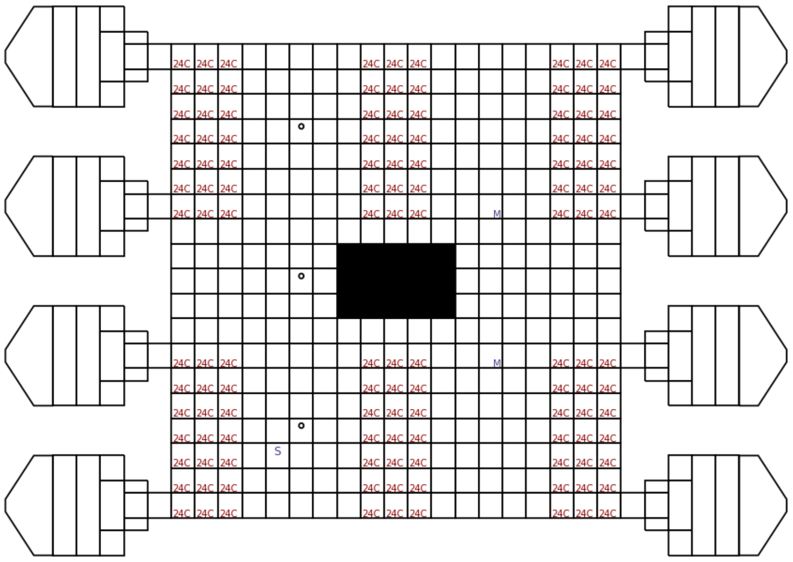
The protocol

The protocol we'll implement involves four reagents: A, B, C, and D. It is defined informally as

1. Dispense drops of reagents A and B and merge them together. Walk the merged drop around for 10 seconds to ensure mixing.
2. Split the merged drop in two and merge the resulting drops with a drop of reagents C and D respectively. Mix these drops by "shuttling" (stepping back and forth) 10 times.
3. Heat the combined drops at 80°C for 30 minutes.
4. Measure each heated drop using an ESELog sensor.
    a. If the mean voltage read on the E1D1 channel is greater than 70V, the drop passes and should be preserved for later testing.
    b. Otherwise, the drop fails and is waste.

The board

The board to be used is the one shown above, repeated more cleanly here:



- The board contains a 19-by-19 array of pads, numbered from pad (1, 1) in the low left-hand corner to pad (19, 19) in the upper right-hand corner.
- There is a 5-by-3-pad dead region in the center of the board. These are pads that cannot be turned on and which, therefore, must be avoided when moving drops.
- The board contains eight wells, numbered 1 to 4 from top to bottom on the left-hand side of the board and 5 to 8 from top to bottom on the right-hand side.
    - We will be using wells 3, 4, 7, and 8 as input wells and well 5 as a waste (output) well.
- The board contains six heating zones, each controlled by a heater, in three columns of two zones each. The left-most column contains heater number 1 on top and 2 on the bottom, the middle column contains heaters number 3 and 4, and the right-most column contains heaters number 5 and 6.
    - We will be using the heating zone on the bottom in the middle, controlled by heater number 4.
- We have available an ESELog sensor, capable of making voltage readings along several channels. The sensor's target is configured to be pad (5, 3), shown by an "S" on the figure.
- The board has three extraction ports, numbered from 1 to 3 from top to bottom.

  - We will be using the middle port, number 2, to extract successful combinations, potentially for further testing later.
- The board also has two magnets, numbered 1 and 2 from top to bottom.
  - We will not be using them.

The code

Rather than overwhelm the reader with the entirety of the example at once, we'll build it up step by step. The entire file, **example.dml**, will contain three informal sections:

1. At the top of the file, we will define the *parameters* of the protocol, things like the reagents to use, the well assignment for each reagent, the temperature to incubate at, and the time to walk while mixing. Putting these together at the top makes them easy to find and modify and means we can avoid using what computer scientists call "magic numbers" in the protocol itself.
2. Next we have the definitions for functions that the protocol will want to make use of.
3. Finally, we have the definition of an action called ***run_protocol***, which, when run, runs our protocol. The action will be written so that it can easily be run multiple times.

The overall structure of the file will be

In file example.dml:

```
/*****************************
 * Our first protocol
 *
 * Author: Evan Kirshenbaum
 ****************************/

// Protocol parameters

// Helper functions

define run_protocol {
   // The body of the protocol
}
```

Comments

At the top of the file, we see the two types of comments available in DML. People familiar with programming languages like Java and C++ will be familiar with both of them:

1. *Block comments* are introduced by `/*` (slash star) and contain all characters up to and including the next following `*/` (star slash), even if this runs over multiple lines. Note that

these comments do not nest. That is, if you have code that includes block comments and try to "comment it out" by using a block comment, the new comment will end at the first star-slash it sees. For this reason, block comments are typically used for information blocks as shown above.

2. The more common *end-of-line comments* begin with `//` (slash slash) and run to the end of the line.

In either case, comments are completely ignored by the language.

Names

The definition of the protocol action:

```
define run_protocol {
   // The body of the protocol
}
```

is introduced by the keyword **`define`** followed by the name of action being defined, in this case "***run_protocol***". Names in DML can contain letters, digits, and underscores, but they may not begin with a digit and they may not consist solely of a single underscore. In addition, they may end with a single question mark (`?`). Names in DML are case sensitive, so ***run_protocol*** is different from ***Run_Protocol***. There are a number of keywords that can't be used as names.[3] The compiler will complain—likely in a very cryptic way—if you try.

Function definitions

The **`define`** keyword is used to define functions (aka "macros"), which may take arguments and may return values when invoked. A function that takes no arguments and returns no value may be referred to as an *action*.

Following the action name, the body of the action is given as a sequence of *statements* between braces `{ … }`. Several types of statements will be shown below. When the action is invoked, the statements will be executed in sequence.

Whitespace

One other thing to note up front is that *whitespace* — spaces, tabs, and line breaks are (almost) completely ignored. The only exceptions (that spring to mind) are (1) spaces and tabs within string literals are preserved (line breaks are illegal there) and (2) at least one whitespace character (or, I guess, comment) is required between two words if not having it would be read another way.

[3] Although there are also a lot of keywords that can be used as names, because the compiler can tell that they aren't being used as keywords.

As an example of the second, the **`define run_protocol`** in the above example could not have been written as **`definerun_protocol`**, as the compiler would see that as one long name.

Step 0: Setting things up

The first thing the protocol will want to do is to ensure that the wells contain the appropriate reagents.

In file example.dml:

```
// Protocol parameters

reagent A = reagent "A";
reagent B = reagent "B";
reagent C = reagent "C";
reagent D = reagent "D";

well A_well = well #3;
well B_well = well #4;
well C_well = well #7;
well D_well = well #8;
well waste_well = well #5;

define run_protocol {
   A_well : require(1 drop of A);
   B_well : require(1 drop of B);
   C_well : require(1 drop of C);
   D_well : require(1 drop of D);

   waste_well’s reagent = waste;

   // more to come
}
```

Variable declarations

In the parameters section, we declare several variables and give them values. Since these variables are declared at the top level of the file, they are considered to be *global variables* and can be referenced from anyplace in the file (unless there is another declaration of a variable with the same name that “shadows” one of them). Variable declarations all have the form

```
type name = initial-value;
```

where the initial value (and the preceding equal sign) may be omitted. (If an initial value is not given, you will get an error if you try to use the value of the variable before one has been assigned to it.) Variable declarations, like all statements that don’t end with **`{ … }`** blocks, end with a semicolon (`;`).

Reagents

In the case of

```
reagent A = reagent "A";
```

the variable being declared is called **`A`** and its type is **`reagent`**. The **`reagent`** type refers to the kind of liquid contained in a drop or well, without respect to its quantity. The initial value expression says that the initial value of **`A`** is the reagent whose name is “A”. Note that if you use the expression **`reagent "A"`** multiple times, you will get the same reagent each time.

After declaring the reagents we will use, we declare the wells that we will use to store them. In

```
well A_well = well #3;
```

we declare a variable named **`A_well`** whose type is **`well`** and which refers to well number 3 on the board. Note that there is no inherent linkage between the reagent variable being **`A`** and the well variable being **`A_well`**. It will be up to us to make the linkage explicit later on.

Numbered objects

The **`well #`** syntax (and, similarly, with **`heater #`**, **`extraction point #`**, and so on) is used to identify a particular well. The argument does not have to be a constant, but can be any integer value, so if we had a variable **`n`** holding an integer, we could refer to **`well #n`** or even **`well #(n+1)`**. In this case, we are specifying that variable **`A_well`** will refer to the third well from the top on the left-hand side of the board.

Numeric types and literals

Since we’ve seen our first literal number here (**`3`**), let’s take a minute to talk about numeric types and literals. Integers are elements of the **`int`** (or integer) type. Integer literals are sequences of digits (**`0`** through **`9`**). Fore readability, they can also contain underscores, so you can write, e.g., **`1_000_000`** as equivalent to **`1000000`**.[4] Negative literals are specified by preceding them with a minus sign (**`-`**), as **`-27`**.

[4] Unfortunately, there are too many situations in which two literal integers could be separated by a comma to allow commas to be used as a separator.

Real numbers are elements of type **`real`** (also specifiable as **`float`**). An **`int`** can always be provided when a **`real`** is required. If you need to convert a **`real`** to an **`int`**, you can explicitly say **`round(x)`**, **`floor(x)`**, or **`ceil(x)`**.

Real literals include a decimal point (`.`) and must have at least one digit on each side of the decimal point. Real literals may also end with **`e`** (or **`E`**) followed by an integer (the *power*), which specifies that the number should be multiplied by ten raised to the power. For example, **`2.0e3`** is another way of writing **`2_000.0`** and **`1.5e-2`** is equivalent to **`0.015`**. If the power is given, the decimal point can be omitted, so **`2.0e3`** could just have been written as **`2e3`**, but this is still **`2000.0`** (a **`real`**), not **`2000`** (an **`int`**).

Injections

Within the definition of **`run_protocol`**, we start by saying which reagents are going to be associated with which wells and how much of each we're going to need:

```
A_well : require(1 drop of A);
B_well : require(1 drop of B);
C_well : require(1 drop of C);
D_well : require(1 drop of D);

waste_well's reagent = waste;
```

The first four lines make use of a somewhat unusual bit of DML syntax that you'll use a lot. Called an *injection*, an expression of the form **`X : Y`** (two expressions separated by a colon[5]) are evaluated as follows:

- First, **`X`** and **`Y`** are evaluated (in that order). The result of evaluating **`Y`** must be a function that either takes no arguments or that takes a single argument compatible with the result of evaluating **`X`**.
- Next, the result of evaluating **`Y`** is called, passing in the result of evaluating **`X`** as its single parameter. We can say that **`X`** has been *injected into* **`Y`**.
- If this returns a result, that result becomes the result of the entire injection, otherwise the result is the result of evaluating **`X`**.

[5] Or a vertical bar (`|`). The vertical bar is more reminiscent of the Unix shell's "pipe" operator, and I had planned to deprecate the colon in favor of it, since the colon is probably more useful elsewhere, but the colon just looks better to me in this context, so I'm leaving it for now.

That sounds more complicated than it (typically) is, and most of the time, the obvious reading is going to be the correct one. In

```
            A_well : require(1 drop of A);
```

`require(1 drop of A)` evaluates to something into which a well (e.g., **`A_well`**) can be injected.

As we will see in just a bit, injections can be combined into longer *chains*. In **`X : Y : X`**, (the result of evaluating) **`X`** is injected into (ditto) **`Y`**, and the result of *that* is injected into (still ditto) **`Z`**. This is most often used to define potentially sequences of actions to be applied to a drop.

The left-hand side of the colon in

```
            A_well : require(1 drop of A);
```

is straightforward. It refers to the current value of **`A_well`**, which, unless somebody changes it, will be well number three.

Liquids

In the right-hand side, we see an expression **`1 drop of A`**. This results in a value of type **`liquid`**, which represents a specific quantity of a reagent. The **`of`** operator takes two values, the first of type **`volume`** and the second of type **`reagent`**.

Physical quantities

The volume here, **`1 drop`** demonstrates the way that DML deals with physical quantities. A number (either a constant or a computed[6] value) followed by units represents a quantity of the type specified by the units. **`drop`** represents the volume of liquid typically dispensed by a given board, but the units here could equally have been **`uL`**, **`ml`**, **`microliters`** or any of several other possibilities. (Try what seems natural. If it isn't recognized, it should probably be added.) Note that the units are only used for specifying the quantity. They don't become a part of the value. So it's perfectly reasonable to compare or add two **`volume`**s that were specified using different units.

In addition to **`volume`**, the system also currently knows about **`time`**, **`frequency`**, **`voltage`**, **`temperature`** (that is, absolute temperature), and **`temperature difference`**. Values of the same quantity type may be compared against one another (**`v1 < v2`**), added to or subtracted from one

[6] Note that in programming terms, the units "bind tighter" than things like addition, so an expression like **`x+1 uL`** will try to add **`1uL`** to **`x`**, which is fine if **`x`** is a volume, but if **`x`** is a number, you will want to say **`(x+1)uL`**.

another, and multiplied or divided by **`real`** values. In addition a **`real`** value divided by a **`time`** becomes a **`frequency`** and vice versa.[7] You can get reciprocal units by using **`per`**. **`3 per second`** is a **`frequency`** and is equivalent to **`3 Hz`**.

`require` expressions

When applied to a well, the expression **`require(L)`**, for some **`liquid L`**, goes through the following steps:

1. First, the system checks to see whether the reagent associated with the well is the same as the one in the liquid required. If it isn't, the system's pipettor[8] is asked to empty the well. If a **`volume`** is passed in rather than a **`liquid`**, this step is skipped, and the well's reagent is used.
2. Next, the current contents of the well are checked to see if the volume in the well is sufficient. If it isn't, the pipettor is asked to add liquid to the well to reach the desired level.

If we had added a second parameter, a volume, to the **`require`** call, e.g.,

```
A_well : require(1 drop of A, 10uL);
```

whenever we determine that we have less than a drop of reagent A in the well, the pipettor will be asked to fill it so that it has 10 µL. This can be useful if a protocol is going to be run multiple times. The first time, the pipettor will be asked to add 10 µL, but the next time there will be more than one drop left, so nothing further will happen until the well gets sufficiently depleted.

In any case, when the statement is done, well number three will be guaranteed to have at least one drop of reagent A. Note that the first argument to **`require`** does not need to be the amount that will be dispensed. If the board you're using can't dispense from a well unless there is at least, say, 5 µL of reagent in it, use **`5uL`** as the parameter.

Function calls

To call a function, write the name of the function followed by any arguments the function may take in parentheses and separated by commas, as **`require(1 drop of A)`**, **`f(1, 2V, r)`**, or **`g()`**.

[7] The exception is that **`temperature`** values do not allow normal arithmetic. You can subtract one **`temperature`** from another, yielding a **`temperature difference`**, and you can add or subtract a **`temperature difference`** from a **`temperature`**, yielding another **`temperature`**.

[8] If the system doesn't have an automated pipettor, a dialog box will probably pop up asking the user to do the transfer manually.

If the function is an *action* (one that takes no arguments and returns no value), the parentheses are optional when it is used as a statement.

Note that injections are another form of function call, and all injection targets are known to take either no arguments or one argument (the value being injected), so the parentheses are not required (or, for that matter allowed). In an injection like

```
A_well : require(1 drop of A);
```

the injection target isn't **`require`**, but rather the result of calling **`require(1 drop of A)`**, which is itself a function that takes a **`well`**. Indeed, that statement could have been written as

```
require(1 drop of A)(A_well)
```

but it wouldn't have been as easy to read.

And let that be a warning that I won't always be telling the full truth here. When I said that what comes before the parentheses is a name, that doesn't tell the whole story. It's actually any expression that evaluates to a function, and that will, in most cases be a name, but there are a number of functions that take **`injectable`** parameters (described below), and when those parameters are omitted in a call, the result is a one-argument function that is intended to be used as an injection target (as with **`require`** here), but which can also be used directly.

The `waste` **reagent**

The last statement in this block is different:

```
waste_well's reagent = waste;
```

For the waste well (well number 5), we don't actually need anything in there, but we do want to say that anything that goes in there is waste. **`waste`** (or **`waste reagent`** or **`the waste reagent`**) is a special predefined **`reagent`** value that has the property that whenever its mixed with something else, the result is **`waste`**. When drops merge together or when drops enter wells, the system keeps track of the reagent of the resulting mixture. (You can also say things like **`A+B`** or even **`A+2*B`** to create combination reagents yourself, but typically you can leave it to the system to keep track of things.) Normally, when a drop goes into a well whose reagent doesn't match its reagent, you will get a warning. By specifying that the well contains **`waste`**, that warning is suppressed, because anything combined with **`waste`** is **`waste`**.

Attributes

This statement also demonstrates the DML notion of *attributes*. Many objects have values associated with them, and the way you refer to an attribute **`attr`** for an object **`obj`** is to say **`obj's attr`**.[9] In addition to its **`reagent`**, a **`well`** also has a number of other attributes including **`number`**, **`gate`**, **`exit pad`**, **`exit direction`**, **`volume`**, **`contents`** (a **`liquid`**), **`capacity`**, and **`remaining capacity`**. As the foregoing (incomplete) list shows, an attribute name may consist of multiple words. There may also be multiple ways to refer to the same attribute. For example, **`exit direction`** may also be referred to as **`exit dir`**.

Assignments

The final thing the statement demonstrates is *assignment*. An expression **`v = X`** assigns (the value of) **`X`** to **`v`**, which may be either a variable or, as here, an attribute of an object. Note that not all attributes are assignable. For example a well's **`number`** or its **`capacity`** are constants, and its **`remaining capacity`** is computed at runtime but not directly assignable.

Step 1: Mixing the first drop

Now that we have the wells set up, we can proceed to step one of the actual protocol:

1. Dispense drops of reagents A and B and merge them together. Walk the merged drop around for 10 seconds to ensure mixing.

We'll do this in two pieces to make it easier to explain what's going on. First, we'll create the merged drop:

[9] You can also say **`obj.attr`**, but I find the possessive notation more intuitive. After having the compiler complain enough times when copying and pasting from this document, you can also say **`obj’s attr`**, with a curved apostrophe.

In file example.dml:

```
// Protocol parameters

pad pComb1 = (5, 4);

define run_protocol {
   // stuff we've seen already

   drop d1;
   [[
      d1 = A_well : dispense drop
                  : to pComb1
                  : accept merge from south
                  ;
      B_well : dispense drop
             : to pComb1 + 2 south
             : merge into north
             ;
   ]]

   // more to come
}
```

Pads

`pComb1` (the first combination pad) is a `pad` which represents where this first merge will take place. It's defined as `(5,4)`, the pad whose `x coordinate` (or `column`) is 5 and whose `y coordinate` (or `row`) is 4, remembering that the pad in the lower left corner is `(1,1)`. The syntax `(x,y)` specifies a pad at those coordinates, which may, of course, be complicated expressions.

Drops

Now let's look at what's going on in the protocol itself. First we declare a `drop d1`, but we don't give it a value yet. A `drop` represents a `liquid` (that is to say a `volume` of a `reagent`) at a particular `pad`. Note that the drop maintains its identity as it moves around the board, although it may lose it when it merges with other drops.

Now on to the fun part. For now, we'll ignore the funny `[[ … ]]` syntax and look at the two statements between the funny brackets. The first

```
      d1 = A_well : dispense drop
                  : to pComb1
                  : accept merge from south
                  ;
```

dispenses a drop from `A_well`, walks it to the pad specified by `pComb1` (that is, `(5,4)`), and waits for a drop to merge with it. The result of that whole injection chain, the drop resulting from the merge, is assigned to `d1`.

Dispensing drops

Looking more closely, we first see **`A_well : dispense drop`**. This injects well number three into **`dispense drop`**, the result of which will be a drop containing 1 drop (whatever that means on this board) of reagent A situated at well number three's **`exit pad`**, **`(1,7)`**.

Moving drops

Next, this drop is told to walk to **`pComb1`** which is the pad at column 5, row 4. It does this by first walking to row 4 and then to column 5. If, for some reason, it was important to do the motion in the other order, we could be more specific and say

```
: to column pComb1's column
: to row pComb1's row
```

The result of this is the same drop that was dispensed, and it is injected into **`accept merge from south`**. There are a couple of things to mention here.

Directions

The first is that directions are a first-class type in DML (called **`direction`** or simply **`dir`**). There are two equivalent sets of **`direction`** constants: **`north`**, **`south`**, **`east`**, **`west`** and **`up`**, **`down`**, **`right`**, **`left`**. Use whichever seems more natural and don't worry about being consistent. Given a **`direction d`**, you can also compute **`d turned around`**, **`d turned right`** (or **`clockwise`**) and **`d turned left`** (or **`counterclockwise`**). Each of these results in a new **`direction`**.

Merging drops

Now that we know what **`south`** means (although it was probably already clear), let's look at what **`accept merge from south`** means.

Basically, it means that it's going to wait for a drop on the pad two pads to the south of it (i.e., in our case, a pad at **`(5,2)`** to indicate that it desires to merge into it. The other drop will indicate this by moving to the drop and injecting the drop into **`merge into north`**. Why *two* pads to the south? Well, to prevent drops from running into one another and accidentally merging, DML assumes that the underlying system requires that drops maintain an empty pad on all sides (including diagonally). This allows the system to provide at least a primitive traffic control so that in most cases drops can move around the board without worrying about one another, yielding when necessary.[10]

In any case, when both drops are in position and have indicated their desire to merge, the one invoking **`merge into`** is absorbed by the one invoking **`accept merge from`**, and the resulting larger drop will be at the pad of the one invoking **`accept merge from`** (and will, in fact, be the identical drop).

So we've got a drop of A in position. So all we need is a drop of B to get in position and be injected into **`merge into north`**. This is exactly what the second statement does:

```
B_well : dispense drop
       : to pComb1 + 2 south
       : merge into north
       ;
```

The only thing that's new here is that instead of moving **`to pComb1`**, this drop moves **`to pComb1 + 2 south`**. As is, hopefully, obvious, this is the pad two rows below **`pComb1`**. The value of **`2 south`** is of type **`delta`**, which represents a number of steps in a direction. This could also have been written as **`south 2`**[11] If the direction isn't a constant, you can use the slightly more awkward **`2 in direction d`** (or **`in dir`**). Note that any time you need a **`delta`**, you can pass in a **`direction`**. **`south`** is equivalent to **`1 south`**.

One other thing to note is that the result of **`merge into south`** is *also* the merged drop. That is, both **`accept merge from`** and **`merge into`** get the same drop as the value. Because of this, you can extend the injection chain of either one to encompass more actions. **But!** It is almost certainly a really bad idea to do this for both of them. Which one you continue with (if either) will depend on what makes sense in your protocol (that is, does it make more sense to accept the merge and then keep moving or to merge into the other drop and keep moving). But don't do both.

[10] It doesn't always work, and sometimes it's necessary to use other mechanisms to avoid drops entering into a state called "deadlock", where two drops are both attempting to yield to one another in a way that will never end. These mechanisms are beyond the scope of this example. Note that DML provides a way to specify that you really want one drop to move right next to another, but it's (intentionally) ugly and cumbersome and, again, beyond the scope of this example.
[11] The two syntaxes aren't quite identical, but they hopefully both do what you expect in the contexts you are likely to use them in, so you won't notice. In particular, **`x+1 south`** is equivalent to **`x+(1 south)`**, while **`south x+1`** is equivalent to **`south (x+1)`**.

So we dispense a drop of A, move it into position. Then we dispense a drop of B and move it into position. Then we merge the two.

Simultaneous execution

Well, almost. Here's where we address the mysterious **`[[ … ]]`** syntax. The actual code is

```
[[
   d1 = A_well : dispense drop
               : to pComb1
               : accept merge from south
               ;
   B_well : dispense drop
          : to pComb1 + 2 south
          : merge into north
          ;
]]
```

The **`[[ … ]]`** is called a *parallel block*, and it says that all of the statements within it are to be executed *at the same time*. So both drops are dispensed, both walk into position, and each informs the other that its ready to merge. The parallel block as a whole ends when all of its statements are done.

In my explanation of **`accept merge`** above, I said that the drop waits for another drop to get into position and call **`merge into`**. That's not quite true. Because we expect that, as in this example, the drops will be moving at the same time, it doesn't matter which of the two drops gets into position first. It will work equally well if the **`merge into`** drop gets there before the **`accept merge from`** drop. Whichever gets there first will wait for the other.

Now that we have the merged drop (which will contain **`2 drops of A+B`**) in **`d1`**, we need to handle the second part of the step: "Walk the merged drop around for 10 seconds to ensure mixing."

A caveat here. The method we'll use is perhaps a bit more verbose that what I would probably use, but it allows me to explain some more features of DML:

In file example.dml:

```
// Protocol parameters

time walk_time = 10s;

define square(int len) -> path {
   return left len
          : down len
          : right len
          : up len
          ;
}

define run_protocol {
   // stuff we've seen already

   path walk_to_mix = square(3);
   repeat for walk_time {
      d1 : walk_to_mix;
   }

   // more to come
}
```

Time

First, we give ourselves a variable, **`walk_time`** that will hold the amount of time to walk. Making it a variable at the top of the file makes it easy to find if we find ourselves wanting to change it later. The variable is of type **`time`** and has a value of **`10s`**. As per usual, the **`s`** could have been **`sec`** or **`secs`** or **`seconds`**, and we could have specified milliseconds, minutes or hours.

The next thing is to decide what we mean by "walk around". What we'll do here is to walk the drop along a square path, and just to be unnecessarily flexible, we'll write a *helper function* to allow us to specify how big that square should be:

```
define square(int len) -> path {
   return left len
          : down len
          : right len
          : up len
          ;
}
```

Declaring function parameters

This defines a function named **`square`** that takes a single parameter, an integer **`(int)`** named **`len`**. As in most programming languages, parameters are specified as a comma-separated list between parentheses. If there are no parameters, the parentheses are optional.

The definition of **`square`** shows one common way of declaring a parameter by writing a type (**`int`**) followed by the name of the parameter (**`len`**). This declares a new variable whose value will be the actual value passed in when the function is called. If there is already a variable or function named **`len`** in the enclosing scope (typically at global level), this one will shadow it, which means that within the function the outer one will not be available, and modifications to the parameter will not affect the outer one. Note that a shadowing parameter—or, indeed, any shadowing declaration—does not need to be the same type as the name that is shadowed.

Unnamed parameters

Alternatively, the parameter can be declared without introducing a name. This can be done in two ways. First, you can give a number rather than a name following the type. If a parameter is declared as, e.g., **`pad 1`** then uses within the body must also be **`pad 1`**. This syntax is sometimes clearer when there are multiple parameters of a given type and there isn't really a good name to give them. The other alternative, when there's only one such parameter is to simply declare the parameter as **`a drop`** (or just **`drop`**). In this case, uses of the parameter will be **`the drop`** or **`drop`**. We will see an example of this below.

Declaring function return types

Return statements

If, as with **`square`**, a function returns a value, the type of that value must be specified after the (optional) parameter block following an dash-greater (**`->`**) arrow. If there is no return value, this is omitted. If there is a return type, all control paths in the function must include a **`return`** statement specifying a value of that type. If there is no return type, **`return`** statements are optional and may not specify a value.

Paths

In the case of **`square`**, the function returns a **`path`** (also called a **`motion`**). This is essentially anything that a **`drop`** could be injected into where the result of the injection would be a **`drop`**.

Following the header, the body of the function is specified as a sequence of statements within braces (**`{ … }`**). In this case, the body contains a single **`return`** statement that returns a **`path`** that says to go **`left`** then **`down`** then **`right`** then **`up`**, each time traveling **`len`** steps, so we wind up right back where we started:

```
return left len
       : down len
       : right len
       : up len
       ;
```

Or does it? If I've done my job, hopefully you're saying "Of course it does." But based on how I described how injections work above, it shouldn't. After all **`left len`** is a **`delta`**, and injecting that **`delta`** into **`down len`** doesn't make a lot of sense.

Compound injections

Except it does. (At least to me.) So what actually happens is that if you write an injection where the second part can take the first but *can* take the result of something injected into the first, what you get is a new injection target that passes the injected object into the first and then passes the result into the second. And that's what's going on here. We don't actually do any injecting, but rather we create a compound injection that can be used later.

Now that we have **`square`** defined, let's use it within **`run_protocol`**. First we call **`square`**, passing in a parameter telling how big a square we want. We store the resulting **`path`** in a local variable:

```
path walk_to_mix = square(3);
```

Loops

Next we use that path to walk the drop **`d1`** for the given amount of time (**`walk_time`**):

```
repeat for walk_time {
   d1 : walk_to_mix;
}
```

This type of statement is called a *loop*, and it is used to perform a sequence of actions potentially more than once. The loop has two parts: its *header*, introduced by the **`repeat`** keyword and its *body*, signified by a block of statements enclosed in braces (**`{ … }`**) or double brackets (**`[[ … ]]`**). In this example, the body of the loop consists of a single statement, an injection in which **`d1`** is passed to the path we got from calling **`square(3)`**, causing the drop to be walked around a 3-by-3 square.

The loops header specifies when the loop should stop repeating. In detail, what happens when a **`repeat`** loop is executed is as follows:

1. The header is checked to see whether the body should be executed. It's possible that the answer may be no even on the first check. If the answer is no, the loop is done.
2. The statements in the body are executed sequentially (for a body specified with braces) or simultaneously (for a body specified with double brackets).
3. Then we go back to step 1 to check to see whether we should execute the body again.

There are several different types of loop headers available, covering commonly needed scenarios:

- **`repeat for 10 minutes`** stops looping after ten minutes have passed. Note that the length of time is computed once when the loop is entered, so if you write **`repeat for t`** and **`t`** is 10 seconds, the loop will end after ten seconds even if **`t`** is changed to be **`1hr`** before that time is up. If the amount of time is zero (or negative), the loop is never entered. Note also that header is only checked once the body is done executing, so if the body of a **`repeat for 5 seconds`** loop takes fifteen seconds to execute, it won't be cut off when the five seconds is up.
- **`repeat 5 times`** runs the body the given number of times, which must be an integer (**`int`**). If the number is not positive, the body is never run. As with time-based loops, the number is evaluated once and stored, so if you say **`repeat n times`**, and **`n`** is ten when the loop is entered, the body will be executed ten times even if **`n`** is changed to 100 before it's done.
- **`repeat until end_ts`** runs the loop body until the *wall-clock time* gets to (or passes) **`end_ts`**, which must be a value of type **`timestamp`**. Values of this type are typically acquired by evaluating **`time now`** (or **`current time`**) and possibly adding or subtracting values of type **`time`** (e.g., **`time now + 1 hour`**).
- **`repeat until n_found >= 10`** continues looping until the expression **`n_found >= 10`** evaluates to **`true`**. Unlike the **`repeat for`** and **`repeat … times`** forms, here the expression is evaluated before each entry to the loop (including the first), so changes to **`n_found`** will be noticed. The provided expression must return a value of type **`bool`** (Boolean), either **`true`** or **`false`**.[12]
- **`repeat while n_found < 10`** is identical to the prior example. Whereas a **`repeat until`** loop executes its body until the condition is **`true`**, a **`repeat while`** loop executes its body until the condition is **`false`**.
- **`repeat with int n = 1 to n_iters`** creates a new variable **`n`** and initializes it to one (or whatever value follows the equals sign). This variable will be available within the loop body. It then evaluates and stores the final value (**`n_iters`** in this case). When the header is checked, the body will be executed unless the value of the variable is greater than the final value. (Note that it is acceptable for the loop body to assign a new value to the variable. This will be reflected in the next test.) After the body is executed, the variable is incremented by its *step size*, which will be one unless another value is specified with a

[12] DML also allows **`True`**, **`TRUE`**, **`yes`**, **`Yes`**, and **`YES`** for **`true`** and **`False`**, **`FALSE`**, **`no`**, **`No`**, and **`NO`** for **`false`**.

`by` clause. For example, **`repeat with real x = 0 to 1 by 0.2`** will repeat the loop with **`x`** taking values 0.0, 0.2, 0.4, 0.6, 0.8, and 1.0.

- If the **`to`** in a **`repeat with`** header is replaced by **`down to`**, the variable is decremented (rather than incremented) by the step size, and the body executes unless the value of the variable is less than (rather than greater than) the final value.
- If no type is specified, instead of creating a new variable, a variable that already exists in the surrounding scope is used. In this case the equals sign and initial value may be omitted and the variable will start from its current value.
- For clarity, especially when no initial value is specified, the keyword **`to`** may be replaced by **`up to`**.

`exit` statements

Within a loop body, an **`exit`** statement tells the system that the loop is finished and should be exited immediately without checking whether to go around again:

```
repeat for 1 hour {
   // Do stuff
   if saw_an_error {
      exit;
   }
   // Do more stuff
}
```

Named loops

If the loop is nested within another loop

```
repeat n times {
   repeat for 10 minutes {
      // Do stuff
      If saw_an_error {
         exit;
      }
      // Do more stuff
   }
}
```

only the inner loop is exited and control passes to the following statement. If you want to exit out of multiple loops, you can add a *loop tag* and specify it in the **`exit`** statement. A loop tag is a name enclosed in brackets (**`[ … ]`**) that precedes the **`repeat`** keyword, as in

```
[outer_loop]
repeat n times {
   repeat for 10 minutes {
```

```
            // Do stuff
            If saw_an_error {
               exit outer_loop;
            }
            // Do more stuff
         }
      }
```

Step 2: Mixing with the other two reagents

At this point, **`d1`** contains a double-sized drop of a mixture of reagents A and B (that is, **`2 drops of A+B`**) and is sitting on pad **`(5,4)`**. We're ready to move on to step two of the protocol:

2. Split the merged drop in two and merge the resulting drops with a drop of reagents C and D respectively. Mix these drops by "shuttling" (stepping back and forth) 10 times.

Here's the code to do this:

In file example.dml:

```
// Protocol parameters

pad pComb2 = (10, 6);
pad pComb3 = (10, 2);

int n_shuttles = 10;

define shuttle(an injectable drop, int n) {
    repeat n times {
       the drop : east : west;
    }
}

define run_protocol {
   // stuff we've seen already

    (eventual) drop d2;
    [[
       d1 : split to south as d2
          : to pComb2
          : accept merge from right
          : shuttle(n_shuttles)
          ;
       d2 : to pComb3
          : accept merge from right
          : shuttle(n_shuttles)
          ;
       C_well : dispense drop
              : to pComb2 + 2 right
```

```
                : merge into left
                ;
          D_well : dispense drop
                : to pComb3 + 2 right
                : merge into left
                ;
    ]]

   // more to come
}
```

We start out by defining parameter variables for the places that the two mixtures take place:

```
pad pComb2 = (10, 6);
pad pComb3 = (10, 2);
```

These are in the lower middle heating zone (zone number four), so the drops will be in position to be heated in the next step. We also create a parameter variable for the number of times we want to shuttle the drops:

```
int n_shuttles = 10;
```

To define what it means to shuttle a drop, this time we'll write a function that does it (rather than, as we did with **`square`**, a function that returns a **`path`** that does it):

```
define shuttle(an injectable drop, int n) {
    repeat n times {
       the drop : east : west;
    }
 }
```

Most of this should already be familiar. We're defining a function named **`shuttle`** that takes two arguments, a **`drop`** to shuttle and the number of times to repeat (**`n`**, an **`int`**), and returns no value. Within its body it performs a loop, repeating the loop body **`n`** times, and within the loop body, we have an injection chain that takes its drop parameter and steps it once to the east (that is, right) and once to the west (left).

There are, however two new bits of DML syntax used in this function definition.

First, the function is so simple that there's really no reason to give its parameter a name. All that's important is that it takes a drop, and so, as mentioned above, we can simply say that its first parameter is **`a drop`**. (We could also have simply said **`drop`**.) Within the body this parameter can be referred to as **`the drop`** (as is done here) or just **`drop`**.

Injectable parameters

Second, the **`drop`** parameter is specified not merely as **`a drop`**, but more specifically **`an injectable drop`**. We want to be able to use **`shuttle`** as an injection target, saying things like

```
d : shuttle(5);
```

for some **`drop d`**. By adding the **`injectable`** keyword preceding a parameter's type, we're saying that if all of the other parameters are specified, what we get back is something that a value of that type can be injected into. Without the **`injectable`** keyword, we have a function that takes two arguments, and we can say

```
shuttle(d, 5);
```

but we can't use this in as the target of an injection. With the **`injectable`** keyword, **`shuttle(d,5)`** will still work, but we can also say simply **`shuttle(5)`** to get something that a drop can be passed to.

There can only be one **`injectable`** parameter, but it doesn't need to be the first one. Note that if the function only takes one parameter, that parameter is automatically **`injectable`**.

Given that, let's take a look at this part of **`run_protocol`**:

```
(eventual) drop d2;
[[
   d1 : split to south as d2
      : to pComb2
      : accept merge from right
      : shuttle(n_shuttles)
      ;
   d2 : to pComb3
      : accept merge from right
      : shuttle(n_shuttles)
      ;
   C_well : dispense drop
          : to pComb2 + 2 right
          : merge into left
          ;
   D_well : dispense drop
          : to pComb3 + 2 right
          : merge into left
          ;
]]
```

Again, most of this should be familiar. We have a parallel block that specifies motion for four drops that will all take place at the same time. One of the drops is drop **`d1`**, which we created previously, two are dispensed from **`C_well`** and **`D_well`** respectively, and the fourth, **`d2`**, we'll get to in a bit. Each of these drops moves into position to merge, two of them calling **`accept merge`** and the other two calling **`merge into`**. The targets of the two merges go on to call **`shuttle`** passing in the value of parameter variable **`n_shuttles`** to tell it how many times to walk back and forth. The block as a whole ends when all four movement chains have finished.

Splitting drops

If you look at the movement of drop **`d1`**, you'll see that it has an extra step. Recall that at this point **`d1`** is a double-sized drop, being the combination of a drop of A and a drop of B. We want to split this into two normal-sized drops (of the same mixture), and we do this by saying **`split to south`**. When this is done, instead of having a double-sized drop at **`(5,4)`**, we now have two normal-sized drops, one at **`(5,4)`** and the other two pads below it at **`(5,2)`**.

`(eventual)` variables

Now let's look at the tricky bit. Variable **`d2`** is declared to not hold a **`drop`**, but rather an **`(eventual) drop`**:[13]

```
            (eventual) drop d2;
```

When you try to use the value of a normal variable and that variable hasn't yet been assigned a value, the system will complain and the program will stop. For an "eventual" variable, on the other hand, if you try to use it before it is set, that thread of control will simply pause until some other thread of control assigns it a value. So within the parallel block, when we say

```
              d2 : to pComb3
                 : accept merge from right
                 : shuttle(n_shuttles)
                 ;
```

nothing will happen until and unless someone running in parallel gives **`d2`** a value. This can be done using an assignment statement such as

```
         d2 = the pad's drop;
```

or it can be done, as here, by adding an **`as`** clause to a **`split to`** expression:

```
              d1 : split to south as d2
                 : to pComb2
```

[13] This could have also been written as **`eventual drop`**, **`(future) drop`** or **`future drop`**.

```
                  : accept merge from right
                  : shuttle(n_shuttles)
                  ;
```

As noted above, this **`split to`** expression will result in a new drop being formed at **`(5,2)`**, but by adding **`as d2`**, it says that that drop should be assigned to the variable **`d2`**. As soon as this happens, the injection of **`d2`** into **`to pComb3`** is able to happen and does.

When all of this is done, there will be two drops on the board. **`d1`** will hold **`1 drop of A+B+2*C`**[14] and **`d2`** will hold **`1 drop of A+B+2*D`**.

Step 3: Heating the drops

Now that we have the two drops, we're ready to move on to step 3:

3. Heat the combined drops at 80°C for 30 minutes.

To be able to show off … er, "explain" … more features of DML, we'll do this in an elaborate manner that gives the user periodic feedback about how much time is remaining.

In file example.dml:

```
// Protocol parameters

heater incubator = pComb2's heater;
temperature incubation_temp = 80C;
time incubation_time = 30 minutes;

define incubate {
    incubator's target = incubation_temp;
    wait until incubator is ready;

    print "Incubating at", incubation_temp,
            "for", (incubation_time : in H:M:S)+".";

    timestamp end_at = time now + incubation_time;

    time pause_length = 1 minute;

    repeat until end_at {
       time remaining = time until(end_at);
       print time now+":", (remaining : in M:S), "left.";
```

[14] The result of mixing equal parts **`A+B`** and **`C`**. Getting equal parts A, B, and C is trickier but will be made straightforward in a future version of DML.

```
        time t = remaining if remaining < pause_length
                         else pause_length;
        wait for t;
     }
     incubator : off;
}

define run_protocol {
   // stuff we've seen already

   incubate;

   // more to come
}
```

As usual, we start out by declaring variables to hold the values that parameterize the protocol:

```
heater incubator = pComb2's heater;
temperature incubation_temp = 80C;
time incubation_time = 30 minutes;
```

We could specify the value of **`heater`** as **`heater #4`**, but instead we'll use the heater associated with the pad we plan on sitting on, **`pComb2`**. If for some reason there is no heater associated with this pad, you'll get an error at run time.

`(maybe)` **values**

The **`heater`** (or **`heating zone`**) attribute associated with a **`pad`** actually returns an object of type **`(maybe) heater`** rather than of type **`heater`**. (The parentheses are optional.) This means that the actual value is either a **`heater`** or the special value **`missing`** (or **`none`**). As noted above, if you try to use a **`(maybe) heater`** as a **`heater`**—the most common use case—and the actual value is **`missing`**, you'll get an error. If you want to check whether a **`pad p`** has a **`heater`**, there are several ways to ask the question. First, you can ask directly about the attribute:

```
if p has a heater { … }
if p does not have a heater { … }
if p doesn't have a heater { … }
```

Alternatively, you can ask about the value itself:

```
if p's heater exists { … }
if p's heater does not exist { … }
if p's heater doesn't exist { … }
if p's heater is missing { … }
if p's heater is not missing { … }
if p's heater isn't missing { … }
```

The latter set are valid any time you have a **`(maybe)`** value, which can also be used for function parameters and variable declarations. For example, you can say

```
define use_if_real(maybe heater h) {
   if h doesn’t exist {
      print "Not a real heater";
      return;
   // Do the work
}
```

and pass in **`p’s heater`** without worrying.

Temperature literals

For the incubation temperature, we set it equal to **`80C`**. Temperatures (both absolute and relative) can be specified with a trailing **`C`** for Celsius or **`F`** for Fahrenheit. The system figures out from context whether it’s a **`temperature`** (or **`temp`** or **`temperature point`** or **`temp point`**) or a **`temperature difference`** (or **`temperature diff`** or **`temperature delta`** or **`temp difference`** or …).[15] This even works with things like

```
temperature t = 80C + 5C;
```

Here, the **`80C`** will be taken to be a **`temperature`** and the **`5C`** will be taken to be a **`temperature difference`**, and the result will be **`85C`**, a **`temperature`**. Of course, you can freely mix temperature systems. **`50F + 10C`** will either be **`20C`** as a **`temperature`** or about **`37.8C`** as a **`temperature difference`**. (Note that if you add two temperature constants directly like that, the second one will always be taken to be a **`temperature difference`**. Also, if you directly compare two temperature constants, they will be taken to be **`temperature`**s.)

Actions at statement level

Inside **`run_protocol`**, this step is trivial:

```
incubate;
```

but there is one subtlety that may not be apparent—and hopefully isn’t. As in most programming languages, a function is invoked by following it with a list of values in parentheses, e.g., **`square(3)`** above. But here, we’re not saying **`incubate()`** (although we could), but rather simply **`incubate`**. Recall that earlier we noted that a function that takes no arguments and returns no result, like

[15] It actually allows it to be ambiguous between the two readings—even if you do math on it—until you try to do something like assign it to a variable or pass it to a function.

`incubate`, is called an *action*. When the value of an expression used as a statement is an action, the action is immediately evaluated.

With that out of the way, all the work happens within the new action **`incubate`**:

```
define incubate {
    incubator's target = incubation_temp;
    wait until incubator is ready;

    print "Incubating at", incubation_temp,
            "for", (incubation_time : in H:M:S), ".";

    timestamp end_at = time now + incubation_time;

    time pause_length = 1 minute;

    repeat until end_at {
       time remaining = time until(end_at);
       print time now+":", (remaining : in M:S), "left.";

       time t = remaining if remaining < pause_length
                     else pause_length;
       wait for t;
    }
    incubator : off;
}
```

Heaters

We'll walk through this step by step. First, we tell the **`heater`** what temperature we want it to go to:

```
    incubator's target = incubation_temp;
```

Heaters are characterized by a number of attributes: **`current temperature`** (or simply **`temperature`**), **`maximum temperature`**, and **`minimum temperature`**[16] as well as their **`target temperature`** (or simply **`target`**), which is the temperature the user has requested the heater go to. This last is the only one a program can modify. The target is actually a **`(maybe) temperature`**. If the value is **`missing`**, then the heater is to go to the ambient temperature.

[16] Where **`temperature`** can be replaced by **`temp`** and **`minimum`** and **`maximum`** can be simply **`min`** and **`max`**.

Note that when we set a heater's **`target temperature`**, this doesn't necessarily mean that it will need to heat up. If the heater's **`current temperature`** is already above the desired target, the heater will turn off until it cools off to the desired point.

Testing properties (`is` expressions)

Once we tell the heater to set its temperature, we wait until it gets there:

```
wait until incubator is ready;
```

An expression of the form **`X is Y`** requires that **`Y`** is a *property*, a function that can take **`X`** and return a Boolean (**`bool`**) value. You can use **`X is not Y`** or **`X isn't Y`** (or, of course, **`not X is Y`**) to ask the opposite question.

Heaters have two defined properties: **`ready`** is true if the heater is maintaining its temperature at or near its designated target, which is not **`missing`**. **`ambient`** is true if the heater's target is **`missing`** and its current temperature is below some (possibly dynamic) threshold set by the board.

`wait` expressions

A statement of the form **`wait until condition;`** pauses the current thread of control until **`condition`** is **`true`**. The condition is re-checked after each tick of the board's clock.[17]

`print` expressions

Now that the heater is at the temperature we want, we'll notify the user that we'll probably be here for a while:

```
print "Incubating at", incubation_temp,
      "for", (incubation_time : in H:M:S)+".";
```

When used as a statement, a **`print`** expression takes one or more values, separated by commas, and prints them, separated by spaces. The values can be of any type. In this example, we see four values.

[17] Note that this means that if you pause the clock, e.g., by saying **`pause the clock`** or **`clock : off`**, this thread of control will be blocked until the clock is resumed (**`resume the clock`** or **`clock : on`**).

String literals

The first and third arguments here are string literals (that is, literals of the `string` type), which are written as sequences of characters between double quotes (`"` … `"`)[18] The characters that make up a string can be any character except double quotes or line break characters (carriage returns or newlines). Within the string literal, you can also include various *escape sequences*, each of which begins with a backslash (`\`): `\t` represents a tab character, `\n` represents a newline, `\r` represents a carriage return, and `\"` represents a double quote. In addition, `\u` followed by exactly four hexadecimal characters represents the Unicode character with that code. For example, `\u05D0` represents the Hebrew letter aleph (א).

Formatted quantities and quantities as numbers in a given unit

For the final argument, we want to print a `time` value, but instead of printing it as a single number followed by units, say `30 min` or `1,800 sec`, we want to format it as `H:M:S`. To do this, we can use `in H:M:S`, either as a function (`in H:M:S(incubation_time)`) or, as we do here, as an injection target. This function returns a `string`, so the result will be `"0:30:00"`. Other available formats are `in H:M` and `in M:S`. If we had wanted to get it formatted as a `string` in units of our choice, we could say, e.g., `incubation_time as a string in hours`, which would return something like `"0.5 hr"`. If we just want it as a number in the units of our choice we could say, e.g., `incubation_time's magnitude in seconds`, which would return `1,800.0` as a `real`. Both `as a string in` and `'s magnitude in` work for any physical quantity, as long as the units match the type.

String concatenations

We also want to end the line with a period. If we were to simply add "." as a fifth argument, the `print` would print a space between the time and the period, so instead, we concatenate the period to the time representation. When the plus (+) operator is used between a string and any value (in either order), the result is the concatenation of the two values, converted to strings if necessary.

Parentheses for grouping

Somewhat surprisingly, it took this long to get an opportunity to point out that in DML, as in pretty much the rest of the world, parentheses (`(` … `)`) are used to make sure that things group together correctly. In

[18] For ease of cutting and pasting and using editors that put them in by default, you can also use smart quotes (“ … ”). They need not be used appropriately.

```
print "Incubating at", incubation_temp,
        "for", (incubation_time : in H:M:S)+".";
```

the parentheses around **`incubation_time : in H:M:S`** are needed, because if they had been omitted, the statement would bind try to do the concatenation before the injection, as if it had been written as

```
print "Incubating at", incubation_temp,
        "for", incubation_time : (in H:M:S + ".");
```

which would not have worked at all, but which would luckily have been caught at compile time.

`print` **expressions as injection targets**

The above description of what **`print`** does, while correct when it is used as a statement as we have here, is a bit of a fib. What actually happens is that when it is evaluated, it returns an action that, when invoked, prints the values. Since an action returned as the value of an expression used as a statement is immediately invoked, the two characterizations are the same. Doing it in this two-step process, however, means that a **`print`** expression can be used as part of an injection chain, as in

```
d : east 2
  : print "The drop is now at", d’s pad
  : north 2;
```

which will print the **`d’s`** location after it has moved east and before it has moved north. (That is, both the printing takes place at that time and the value printed is the drop’s location at that time.)

Now we wait:

```
timestamp end_at = time now + incubation_time;

time pause_length = 1 minute;

repeat until end_at {
   time remaining = time until(end_at);
   print time now+":", (remaining : in M:S), "left.";

   time t = remaining if remaining < pause_length
                 else pause_length;
   wait for t;
}
```

We could do this simply by saying

```
wait for incubation_time;
```

which would pause the current computation for the desired amount of time, but since this is going to take a while, we'll instead give the user periodic feedback of how much time is remaining.

Timestamps

We start by figuring out at what time the pause will end:

```
timestamp end_at = time now + incubation_time;
```

`time now` returns the current wall-clock time as a **`timestamp`**, and when we add **`incubation_time`** to it, we get a new **`timestamp`** that far in the future.

Next, we specify how often we'll print our message or, equivalently, how long we'll pause after each **`print`** statement:

```
time pause_length = 1 minute;
```

Finally we go into a loop that will end at the specified timestamp:

```
repeat until end_at {
   time remaining = time until(end_at);
   print time now+":", (remaining : in M:S), "left.";

   time t = remaining if remaining < pause_length
                 else pause_length;
   wait for t;
}
```

Recall that there are two meanings to **`repeat until`**. If the value given is an expression of type **`bool`** (e.g., **`n < 5`**), the expression will be evaluated each time around the loop and the loop will stop when the value is **`true`**. If, on the other hand, the value is an expression of type **`timestamp`**, it is evaluated once to determine the wall-clock time after which the loop should stop. We use the second meaning here.

Inside the loop, we determine how much time we have left to wait:

```
   time remaining = time until(end_at);
```

`time until(ts)` gives us the amount of **`time`** until the given **`timestamp`**. If the **`timestamp`** is in the past, this will be negative. Similarly, **`time since(ts)`** gives us the **`time`** since the **`timestamp`**, which, if the **`timestamp`** is in the future, will be negative.

We print the remaining time:

```
                print time now+":", (remaining : in M:S), "left.";
```

this time using **`in M:S`** to format it as minutes and seconds.

Conditional expressions

Next we calculate the time we will wait until the next time we print. We've specified that **`pause_length`** is to be **`1 minute`**, but we don't want to wait that long if that's more time than we have left, so we use a conditional expression to determine the actual amount of time to wait:

```
time t = remaining if remaining < pause_length
                   else pause_length;
```

An expression of the form **`X if C else Y`** first evaluates **`C`** and then evaluates either **`X`** or **`Y`** (but not both) depending on the value of **`C`**.

Once we know how long we want to wait, we wait for that amount of time:

```
wait for t;
```

Binary components and states

When the loop exits (i.e., after **`time now`** reaches or passes **`end_at`**), we're done incubating, and we can turn off the heater:

```
incubator : off;
```

Here we see another pair of useful concepts. The class **`binary component`** (or **`binary cpt`** or simply **`binary`**) encompasses all classes of thing that can be turned on and off. This includes **`heater`**, as well as **`pad`**, **`magnet`**, **`chiller`**, **`fan`**, **`power supply`**, **`well pad`**, and **`well gate`**. It also includes the unnamable class returned by **`the clock`**. All binary components have a **`state`** attribute whose value is of type **`binary state`** (or simply **`state`**), which has constants **`on`** and **`off`**. You can set this attribute directly (e.g., **`incubator's state = off`**), but it's more common to use **`on`** and **`off`** (or **`turn on`** and **`turn off`**) as injection targets. You can also say

```
incubator : toggle
```

(or **`toggle state`**) to flip from **`off`** to **`on`** or vice versa.

To check whether a **`binary component`** is in a particular **`state`**, you can use **`c is on`** or **`c is off`**.

Turning heaters on and off

For a **`heater`** specifically, setting its **`state`** to **`off`** (by any of these means) is equivalent to setting its **`target temperature`** to **`none`**. The heater turns off and is allowed to return to ambient temperature. Setting the state to **`on`**, on the other hand, is slightly different. This is interpreted as a request to set the heater's **`target`** to whatever it was before the last time it was turned off. So, once you've established a **`target`**, you can switch between states without having to reassert the target temperature.

Step 4: Analyzing the drops

Finally, the drops are ready to be analyzed.

4. Measure each heated drop using an ESELog sensor.
    a. If the mean voltage read on the E1D1 channel is greater than 70V, the drop passes and should be preserved for later testing.
    b. Otherwise, the drop fails and is waste.

Here's how we'll do that:

In file example.dml:

```
// Protocol parameters

voltage reading_target = 70 V;
extraction port product_port = extraction port #2;


define run_protocol {
   // stuff we've seen already

   define finish_up(injectable drop d) {
      eselog e = the board's eselog;

      d : to e's target;

      local r = e : take a reading
                  : write to csv file;
      voltage v = r's e1d1_on;

      if v < reading_target {
         print d's reagent, "is good!", "("+v+")";
         d : to product_port : transfer out;
      } else {
         print d's reagent, "is bad.", "("+v+")";
         d : become waste : to waste_well : enter well;
      }
    }

    [[
       d2 : finish_up;
       d1 : finish_up;
    ]]

    prompt "Finished at", time now;
}
```

There are two parameters relative to this phase. The first is the voltage cutoff that we'll use to distinguish good reagents from bad ones:

```
voltage reading_target = 70 V;
```

Extraction ports

The second is the **`extraction port`** we'll use to extract the good drops for later testing:

```
extraction port product_port = extraction port #2;
```

An **`extraction port`** (aka, **`extraction point`**, **`extraction hole`**, or simply **`hole`**) is a hole in the board's lid that can be used to add liquid to or remove liquid from the pad below. In our case, we'll be using the port number `2`, above pad **`(7,10)`**. To transfer liquid in through an extraction port, you can say

```
ep : transfer in 2uL of r;
```

To transfer out, move the drop to the extraction port and call **`transfer out`**:

```
d : to ep : transfer out;
```

This will remove the whole of the drop, and the drop will no longer be considered to be on the board. If you only want part of the drop removed, you can specify the amount to remove:

```
d : to ep : transfer out(0.5uL);
```

This will ask the pipettor to remove the specified volume, and if it is less than the drop's volume, the drop will shrink by that much.

The last step of the protocol is implemented by the **`finish_up`** action, which processes one drop and which we'll get to in a minute. With it, we can simply say

```
[[
   d2 : finish_up;
   d1 : finish_up;
]]
```

to run each of our two drops through **`finish_up`**.

Note that **`finish_up`** will require walking the drop to the pad the sensor uses to take a reading and then sitting there while the reading is taken before moving away. But because of the traffic control of the underlying system, we can simply have both drops execute this action at the same time. One of them will get there first, and the other will wait, two pads away, until the first drop leaves.

Dealing with deadlock

It is, of course, possible that you'll get unlucky and the default paths used to walk to the target pad cause the two drops to "deadlock" by getting into a state in which each is waiting for the other to get out of the way. It is also possible that the second, waiting, drop may block the first drop's default path to get off of the sensor's pad. In either of these cases, you may have to be more specific about the paths taken, e.g., by adding a **`to column`** or **`to row`** component to the movement to ensure that they can't get in each other's way. Because of this possibility of needing to tweak paths, it's usually a good idea to run you protocol in simulation before running it with a physical board and, especially, before running it using expensive and/or irreplaceable reagents.

Finally, we let the user know we're done and when we finished.

```
                prompt "Finished at", time now;
```

`prompt` **expressions**

In this case, I've chosen to use a **`prompt`** statement rather than a **`print`** statement, both in order to introduce it and because it is more eye-catching. **`prompt`** is just like **`print`**, but instead of writing the message to the console, it pops up a dialog box and requires the user to acknowledge it.

Like **`print`**, **`prompt`** can be used in injection chains, and this can be useful when you require the user to do something before you can proceed:

```
          d  : move_into_position
             : prompt "Ensure the filter is in place."
             : do_the_thing_that_requires_the_filter
             ;
```

Unlike **`print`**, **`prompt`** can be used without any expression, in which case the dialog box contains a default message. Because one of its functions is waiting for the user to do something, **`prompt`** can also be written as **`pause for user`** or **`wait for user`**.

Local functions

The first thing to notice about the **`finish_up`** action, which does the actual work, is that we've put its definition within the definition of **`run_protocol`**. This has a couple of consequences. First, it means that **`finish_up`** can only be called from within **`run_protocol`**. Outside an invocation of **`run_protocol`**, the name is simply not defined (or it may be defined to be another function or variable). Second, it means that **`finish_up`** has access to any variables within **`run_protocol`** (including any parameters it may have been called with) that were declared before it in the body of **`run_protocol`**.

Defining local functions like this for things like protocol phases, which nobody outside of the protocol should want to call, can be a useful technique. It also means that several local functions or actions can all see the parameters to the enclosing function and any variables declared at the beginning of it. This means that these variables can be used to store state between invocations of the local actions:

```
define process(a drop) {
   int n = 0;
   define trace {
      n = n+1;
      print the drop+":", "Times called:", n;
   }

   repeat for 10 minutes {
      the drop : do_the_thing;
      trace;
   }
}
```

Here, **`n`** is used to keep track of the number of times we've gone around the loop, and **`trace`** both refers to and increments it, as well as referring to **`the drop`**, a parameter to **`process`**.

Another thing to note about that example is that each time **`process`** is invoked, a new environment containing **`the drop`** and **`n`** is created, and a new **`trace`** is created that refers to that environment. This means that even if we call **`process`** in parallel:

```
[[
   d1 : process;
   d2 : process;
]]
```

each one will have its own **`drop`**, and each one's **`trace`** will modify its own **`n`**.

Now, let's look at what's going on inside of **`finish_up`**.

```
   define finish_up(injectable drop d) {
      eselog e = the board's eselog;
```

```
               d : to e's target;

               local r = e : take a reading
                           : write to csv file;
               voltage v = r's e1d1_on;

               if v < reading_target {
                  print d's reagent, "is good!", "("+v+")";
                  d : to product_port : transfer out;
               } else {
                  print d's reagent, "is bad.", "("+v+")";
                  d : become waste : to waste_well : enter well;
               }
             }
```

The board

In the first step

```
               eselog e = the board's eselog;
```

we use **`the board`** to get access to the sensor we need. This form (or just **`board`**) returns a value representing the board as a whole, which is mostly useful for its attributes, which can be used to get various components that may be present in the system. Besides **`eselog`**, these attributes include **`power supply`**, **`fan`**, and **`clock`**. Aside from **`clock`**, these all return **`(maybe)`** values, so you can say things like **`if the board has a power supply`** or **`if the board's fan exists`**.

Sensors

The value of **`e`** represents the board's ESELog. It's type, **`eselog`**, is a subtype of **`sensor`** and shares with it all of the things that are common to all sensors, several of which we'll use below. All **`sensor`** objects have a **`target`** attribute, which is a **`(maybe) pad`** that gives the pad, if any, the sensor will take its reading from. This attribute can be set to a new value by assignment, but note that this should be done in response to the hardware changing, not in an attempt to change the hardware, as it will not do so. If you wish to engage the hardware to ensure that it is looking where it should be, you can say **`s : aim`** (or **`s : aim(p)`** for some pad **`p`**). For an ESELog, this will turn on the sensor's targeting laser and prompt you to confirm when it's in the right place. Note that if an argument is given to **`aim`**, this does not change the sensor's **`target`**.

The main thing you do with sensors is to use them to take readings:

```
          s : take a reading
```

(or **`take reading`** or **`take readings`**). This can take two extra parameters, both optional. The first is an integer giving the number of samples to take. If it is not given, it defaults to the value of the sensor's **`n samples`** attribute. The second is either a **`time`** or a **`frequency`** giving an indication of the rate at which the samples should be taken, measured from the start of one to the start of the next. If not given, this defaults to the sensor's **`sampling rate`** (or **`sampling rate`**), a **`frequency`**, or its **`sampling interval`** (or **`sample interval`**), a **`time`**. Both of these are views of the same value, so changing one changes the other. "test"

Once we have the sensor, we walk the drop to its **`target`** pad:

```
d : to e's target;
```

and to take the reading:

```
local r = e : take a reading
            : write to csv file;
```

Writing readings to files

The value that comes back from **`take a reading`** is an **`eselog reading`**, which is a special case of **`sensor reading`**. One of the things that you can do with an **`eselog reading`** is to write it to a CSV file, which can be done with **`write to csv file`** (**`write csv file`**, **`write to file`**, **`write file`**). This can take two optional parameters. The first is a **`string`** specifying the name of the file to use, and the second is a **`timestamp`**, which defaults to the timestamp associated with the first sample in the **`sensor reading`**. The first parameter (or its default) is actually a template for the file name to use and may include indications of where to put in parts of the **`timestamp`**. These substitution specifications are based on those used by **`strftime`**. In Thylacine, the default file name template is **`"eselog-%Y-%m-%d_%H_%M_%S.%f.csv"`**, which substitutes in the four-digit year (**`%Y`**), two-digit month (**`%m`**), two-digit day of the month (**`%d`**), two-digit 24-hour hour (**`%H`**), two-digit minute (**`%M`**), two-digit second (**`%S`**) and six-digit fraction of a second (**`%f`**). More formats can be found at https://strftime.org/.

`local` **variable declarations**

Looking at the declaration of **`r`**, you'll see that while the initial value is of type **`eselog reading`**, we don't say **`eselog reading r`**, but rather **`local r`**. In fact, the type of **`r`** will be **`eselog reading`**. When an initial value is given, as a shorthand, you can give the variable's type as **`local`** to mean "whatever the type of the initialization expression is". This can be convenient, especially for variables that have complicated (or even inexpressible) types, but it should be used sparingly, especially if the variable is going to have a new value assigned later. For instance, if you say

```
local multiplier = 1;
```

and then later say

```
        multiplier = 2.5;
```

the compiler will complain, because the type of **`multiplier`** is the type of `1`, which is **`integer`**, not **`real`**.

Sample types

Now we need to check whether the drop passes or not.

```
                voltage v = r's e1d1_on;
```

Within the **`eselog reading`** are a number of *samples* which can be thought of as like the columns in a spreadsheet table, where the values for each sample the sensor took are like the values for that column in each row.

As an **`eselog reading`**, **`r`** has attributes **`e1d1_on`**, **`e1d1_off`**, **`e2d2_on`**, **`e2d2_off`**, **`e1d2_on`**, and **`e1d2_off`**, all of which are of type **`voltage sample`** and which represent the voltage read long each channel. In addition **`r′s temperature`** is a **`temperature sample`** representing the temperature when the reading was taken, **`r′s ticket`** is an **`integer sample`** representing a serial number given to each sample by the device. And, like all **`sensor reading`**s, **`r′s timestamp`** represents the times the samples were taken.

So if a sample represents a column of values, what can you do with it? Basically, you can use its attributes to find out things about the values. It's attributes include **`mean`** (or **`arithmetic mean`**), **`std dev`** (or **`std deviation`** or **`standard dev`** or **`standard deviation`**), **`median`**, **`count`**, **`min`** (or **`minimum`** or **`min value`** or **`minimum value`**), **`max`** (or **`maximum`** or **`max value`** or **`maximum value`**), **`range`** (**`max—min`**), **`first`** (or **`first value`**), **`last`** (or **`last value`**), **`harmonic mean`**, and **`geometric mean`**. You can also ask if it **`is empty`**.

If you try to convert it to its element type, as we do here, using a **`voltage sample`** as a **`voltage`**, the value that's used is the **`mean`**, so what we get is the mean of the readings along that channel.

You can create your own sample objects. For instance, if you want to compute performance statistics on running a function, you can do something like

```
        time sample s = an empty time sample;
        repeat n times {
           timestamp start = time now
           do_the_thing;
           s : add(time since(start));
        }
        print "It took", s's mean, "+-", s's standard deviation;
```

`an empty time sample` gets you an empty time sample and **`add(t)`** adds **`t`** to it. Samples can be created for any physical quantity type as well as **`temperature point`**, **`timestamp`**, **`integer`**, and **`real`**. Note that in some cases the attribute values may not be of the element type. For instance, an **`int sample`**'s **`mean`** will be a **`real number`** rather than an **`integer`**, and a **`timestamp sample`**'s **`standard deviation`** will be a **`time`** rather than a **`timestamp`**.

Instead of starting with and **`empty time sample`**, you can give it some initial values as **`a sample containing`** (or just **`sample containing`**) followed by comma separated values with an optional **`and`** before the last one:

```
int sample s = a sample containing 1, 5, and 10;
```

(If there are only two elements, the comma before **`and`** is optional, so you can say **`a sample containing t1 and t2`**). The element type of the sample is inferred from the types of the values given, which all have to be compatible, so **`a sample containing 1 and 2`** is an **`integer sample`**, but **`a sample containing 1 and 1.5`** is a **`real sample`**, since **`1`** can be a **`real`**, but **`1.5`** cannot be an **`integer`**.

Now that we have the value we want to test in **`v`**, the only thing left to do is to compare it and take the appropriate action:

```
if v < reading_target {
   print d's reagent, "is good!", "("+v+")";
   d : to product_port : transfer out;
} else {
   print d's reagent, "is bad.", "("+v+")";
   d : become waste : to waste_well : enter well;
}
```

Conditional statements

Here we see an example of a *conditional* statement. Such a statement is of the form

```
if condition_1 {
   action_1;
} else if condition_2 {
   action_2;
} else if condition_3 {
   action_3;
} else {
   default_action;
}
```

where there may be any number of **`else if`** clauses (including zero) and where the **`else`** clause is optional.[19] The logic is that first **`condition_1`** is evaluated. If it evaluates to **`true`**, **`action_1`** (and all other statements in its block) are executed and the statement is done. If **`condition_1`** evaluated to **`false`**, **`condition_2`** is evaluated, and if it is **`true`**, all of the statements in the second block are executed and the statement is done. This continues through all of the **`else if`** conditions. If none of them evaluate to **`true`** and there is an **`else`** clause, its block is executed.

In our example, we have a single condition, **`v < reading_target`**, and no **`else if`** clauses, but there is an **`else`** clause, so one of the blocks will necessarily be evaluated.

If the test is satisfied, the drop is good, so we say so:

```
print d's reagent, "is good!", "("+v+")";
```

We then walk the drop to the extraction port and instruct the pipettor to remove it:

```
d : to product_port : transfer out;
```

If the test wasn't satisfied, we enter the else block and let the user know"

```
print d's reagent, "is bad.", "("+v+")";
```

and then we walk the drop into the waste well:

```
d : become waste : to waste_well : enter well;
```

Changing a drop's reagent

As noted above, a **`drop`** has a **`reagent`** attribute, and you can change the reagent by setting that value:

```
d's reagent = r;
```

`become r`, as an injection target, is a shorthand for this. Changing the reagent is useful in a couple of situations. First, as in our example, when we've decided that the drop is **`waste`** and we're in the process of walking it to a waste well. Strictly speaking, this isn't necessary, but when there are a large number of drops on a board and there is a GUI showing a representation of what is where, it can be useful to be able to distinguish at a glance between waste drops and drops that are still of interest. Second, when you are building up some product by merging, heating, and otherwise

[19] Programmers familiar with C or C++ should note that the body of each of these clauses is a block, not a statement. The braces (or double brackets) are required.

munging drops, there may be a point at which you can say “Okay, we’ve now got what we were trying to make.” In the Thylacine GUI up to that point, the drop will have been represented by a pie chart of the reagents that make up its components. Changing the reagent to something simpler allows it to be more simply represented.

Entering a well

Finally, the drop calls **`to waste_well`** to walk to the well (or, rather, the well’s **`exit pad`**) and then calls **`enter well`** to go in. It goes without saying that if you inject a drop into **`enter well`** and it isn’t on the exit pad for some well, an error will be raised.

Putting it all together

The foregoing sections have built up the protocol piecemeal over quite a number of pages, so it may seem as though there’s a lot of it, but in fact the whole **`example.dml`** file, comments and all, is only 171 lines long:

File example.dml:

```
/****************************
 * Our first protocol
 *
 * Author: Evan Kirshenbaum
 ****************************/

// Protocol parameters

reagent A = reagent "A";
reagent B = reagent "B";
reagent C = reagent "C";
reagent D = reagent "D";

well A_well = well #3;
well B_well = well #4;
well C_well = well #7;
well D_well = well #8;
well waste_well = well #5;

pad pComb1 = (5, 4);
pad pComb2 = (10, 6);
pad pComb3 = (10, 2);

time walk_time = 10s;
int n_shuttles = 10;
```

```
heater incubator = pComb2's heater;
temperature incubation_temp = 80C;
time incubation_time = 30 minutes;

voltage reading_target = 70 V;
extraction port product_port = extraction port #2;

// For testing

define speed_up {
   incubation_time = 10 seconds;
}

// Helper functions

define square(int len) -> path {
   return left len
           : down len
           : right len
           : up len
           ;
}

define shuttle(an injectable drop, int n) {
   repeat n times {
      the drop : east : west;
   }
}

define incubate {
   incubator’s target = incubation_temp;
   wait until incubator is ready;

   print "Incubating at", incubation_temp,
         "for", (incubation_time : in H:M:S)+".";

   timestamp end_at = time now + incubation_time;

   time pause_length = 1 minute;

   repeat until end_at {
      time remaining = time until(end_at);
      print time now+":", (remaining : in M:S), "left.";

      time t = remaining if remaining < pause_length
                         else pause_length;
      wait for t;
   }
   incubator : off;
}

// The protocol
```

```
define run_protocol {
   // Step 0:

   A_well : require(1 drop of A);
   B_well : require(1 drop of B);
   C_well : require(1 drop of C);
   D_well : require(1 drop of D);

   waste_well's reagent = waste;

   // Step 1. Dispense drops of reagents A and B and merge them
   //         together.  Walk the merged drop around for 10
   //         seconds to ensure mixing.

   drop d1;
   [[
      d1 = A_well : dispense drop
           : to pComb1
           : accept merge from south
           ;
      B_well : dispense drop
           : to pComb1 + 2 south
           : merge into north
           ;
   ]]

   path walk_to_mix = square(3);
   repeat for walk_time {
      d1 : walk_to_mix;
   }

   // Step 2. Split the merged drop in two and merge the
   //         resulting drops with a drop of reagents C and D
   //         respectively.  Mix these drops by "shuttling"
   //         (stepping back and forth) 10 times.

   (eventual) drop d2;
   [[
      d1 : split to south as d2
         : to pComb2
         : accept merge from right
         : shuttle(n_shuttles)
         ;
      d2 : to pComb3
         : accept merge from right
         : shuttle(n_shuttles)
         ;
      C_well : dispense drop
             : to pComb2 + 2 right
             : merge into left
             ;
      D_well : dispense drop
             : to pComb3 + 2 right
             : merge into left
             ;
   ]]

   // Step 3. Heat the combined drops at 80°C for 30 minutes.

   incubate;

   // Step 4. Measure each heated drop using an ESELog sensor.
   //         If the mean voltage read on the E1D1 channel is
   //         greater than 70V, the drop passes and should be
   //         preserved for later testing.  Otherwise, the drop
   //         fails and is waste.

   define finish_up(injectable drop d) {
      eselog e = the board's eselog;

      d : to e's target;

      local r = e : take a reading
                  : write to csv file;
      voltage v = r's e1d1_on;

      if v < reading_target {
         print d's reagent, "is good!", "("+v+")";
         d : to product_port : transfer out;
      } else {
         print d's reagent, "is bad.", "("+v+")";
         d : become waste : to waste_well : enter well;
      }
   }

   [[
      d2 : finish_up;
      d1 : finish_up;
   ]]

   prompt "Finished at", time now;
}
```

CHAPTER THREE: **Things Not Covered**

While I tried to cover as much of DML as I could in a single program, there are still some topics that didn't make it in, and I'll try to cover them here. Since my time at the moment is *extremely* tight, these won't necessarily be in any order (and may be somewhat brief).

Functions

Function definition keywords

In the example, I showed several examples of defining functions, both with and without parameters and with and without return types, all using the **`define`** keyword. In all cases, **`define`** can be replaced by **`def`** (as in Python) or **`macro`** (as it was in an early version of DML, back when it was simply called "the macro language").

In addition, if the function has no parameters and doesn't return a value, you can replace **`define`** by **`action`**, as in

```
action complain {
   print "It didn't work!";
}
```

If the function doesn't return a value (whether or not it has parameters), you can use **`procedure`** or **`proc`**:

```
procedure print_reagent(a well) {
   print the well+"'s" reagent is the well's reagent;
}
```

On the other hand, if it *does* return a value, you can use **`function`** or **`func`**:

```
function double(int n) -> int {
   return 2*n;
}
```

All of these are a matter of personal preference. **`define`**, **`def`**, and even **`macro`** will work in all cases.

Parallel-block functions

All of the examples of function given so far define their bodies using curly-brace blocks (`{ … }`), which evaluate their statements in order. It is also possible to use double-bracket blocks (`[[ … ]]`), which evaluate their statements in parallel:

```
define merge_drops(drop 1, drop 2, dir to_d2) [[
   drop 1 : accept merge from to_d2;
   drop 2 : merge into (to_d2 turned around);
]]
```

Anonymous function values

All of the examples so far include a name following the keyword and occur at statement level. This had the effect of defining the function with that name. But if you omit the name, you can still create a function. It just won't have a name. This can be useful when you want to create a simple function to use as an injection target:[20]

```
d : … : def (drop d) { print "d is at", d's pad; } : …
```

(Yes, this is a bit ugly. Wait until the next section.)

In fact a definition like

```
function double(int n) -> int {
   return 2*n;
}
```

is actual equivalent (mostly) to

```
local double = function(int n) -> int {
   return 2*n;
}
```

When there is no name for a function value, the keyword **`lambda`** is another option.

Expression-bodied functions

As an alternative to providing a (sequential or parallel) block as the function body, you can instead use colon (`:`) followed by an expression, so simple functions can be written as, e.g.,

```
define double(real x) : 2*x;
```

[20] It will become more useful when functions can be used as arguments and return values.

When the body is an expression, specifying the return type is optional. If it is omitted, it will be inferred from the value of the expression.

Expression-bodied functions may also be anonymous, and so the earlier example could have been written as

```
d : … : (lambda(drop d): print "d is at", d's pad) : …;
```

and if you want to change from a drop to its reagent in the middle of a chain, you can simply say

```
d : … : (lambda(drop d): d's reagent) : …;
```

Note that in these examples, the parentheses are necessary to ensure that the following colon isn't considered to be part of the function's body.

Recursive functions

The name of a function (if there is one) is visible within the body of the function, so the function can call itself, as in this definition of the factorial functions:

```
define factorial(int n) -> int {
   return 1 if n < 2 else n*factorial(n-1);
}
```

Unfortunately (at least in the current implementation), to define a recursive function using an expression body, the return type specification is mandatory:[21]

```
define factorial(int n) -> int : 1 if n < 2 else n*factorial(n-1);
```

Without the return type, the compiler can't figure out the type of the recursive call, which is needed to figure out the return type.

[21] Okay, I just tried that and it didn't work. It works if you put the recursive call in parentheses as **`(factorial(n-1))`**, and it works if you put the multiplication in parentheses **`(n*factorial(n-1))`**. Oh, well. One more for the issues list.

Mutually recursive functions

This doesn't work yet. I'm not sure why. The compiler doesn't accept the forward declaration. I think I know how to fix it, but it's not completely trivial.

Sometimes you will have two functions that need to call one another. In this case, you need to add a *forward declaration* for the one that is defined later so that the compiler knows to expect it and what its type will be. This is simply the function header without any body.

For example, the following two functions ping-pong back and forth between one another:

```
define f2(int n);

define f1(int n) {
   print "First:", n;
   if n > 0 {
      f2(n-1);
   }
}

define f2(int n) {
   print "Second:", n;
   if n > 0 {
      f1(n-1);
   }
}
```

Without the forward declaration of **`f2`**, the compiler wouldn't know what to do when it saw the **`f2(n-1)`** call inside of **`f1`**.[22]

Operators

Arithmetic operators

DML has the usual complement of arithmetic operators: **`+`** (addition), **`-`**(subtraction or negation), **`*`** (multiplication), and **`/`** (division). There is currently no exponentiation operator. As is normal, multiplication and division have higher precedence than addition and subtraction, so **`x+y*z`** is equivalent to **`x+(y*z)`**. Negation has the highest precedence, so **`-x+z`** is the same as **`(-x)+z`**. All of the operators have higher precedence than most other things, including injections, but not including unit suffixes, so

[22] That's not quite true. A smarter compiler could look ahead and see what was going to be defined within the block. We don't have a smarter compiler at the moment.

```
… : wait for t + 5 seconds : …
```

is equivalent to

```
… : (wait for (t + (5 seconds))) : …
```

If you want the number of seconds to wait to be `t + 5`, you'll need to add parentheses:

```
… : wait for (t + 5) seconds : …
```

For numbers (`int` and `real`), these work as you'd expect, with the caveat that dividing one `int` by another will result in a `real`.

Physical quantities (which includes things like `time`, `volume`, and `temperature difference`, but not absolute points like `temperature` or `timestamp`) can be added to or subtracted from values of their same type, and they can be multiplied or divided by `real` values. In addition,

- You can add a `timestamp` and a `time` or subtract a `time` from a `timestamp`, resulting in a `timestamp`.
- You can subtract one `timestamp` from another, resulting in a `time`.
- You can add a `temperature` and a `temp diff` or subtract a `temp diff` from a `temperature`, resulting in a `temperature`.
- You can subtract one `temperature` from another, resulting in a `temp diff`.
- You can add a `pad` and a `delta` (or a `direction`) and get the `pad` (which may not exist) that far in that direction. Similarly, you can subtract a `delta` from a `pad` to get the `pad` in the opposite direction.
- You can add two scaled `reagents` (either a `reagent` or a `reagent` multiplied by a `real`) to get `reagent` representing the mixture of the two. This allows you to say things like `2*A+B` to indicate a `reagent` that's two parts `A` and one part `B`. The result will be in simplest form, so if you took that value and added it to `A+2*B`, you'll get `A+B`.
- You can add two `liquids` and get the result (as a `liquid`) of combining the two. The result's `volume` will be the sum of the volumes of the two `liquids`, and its `reagent` will be the result of adding the two reagents, scaled by the relative volumes.
- You can add two `string`s to get their concatenation.
- You can add anything else to a `string` (in either order) and get a `string` that is the concatenation of the `string` and the string representation of the other value.
- You can divide a `liquid` by a `real` to get a `liquid` with the same `reagent` and a scaled `volume`.

Relational operators

Values of any type can be compared to other values of the same time using **`==`** (equals) and **`!=`** (does not equal).

Numbers and physical quantities (including **`temperature`** and **`timestamp`**) can be compared to one another using **<** (is less than), **<=** (is less than or equal to), **>** (is greater than), and **>=** (is greater than or equal to).

Relational operators have lower precedence than arithmetic operators, so

```
x < y + 2
```

is the same as

```
x < (y + 2)
```

Boolean operators

DML has the normal Boolean (or "logical") operators: **`not`**, **`and`**, and **`or`**, all of which require operands of type **`bool`**. **`not X`** is **`true`** when **`X`** is **`false`**, and vice versa. **`X and Y`** is **`true`** when both **`X`** and **`Y`** are **`true`** and **`false`** if either is **`false`**. **`X or Y`** is **`true`** when either **`X`** or **`Y`** is **`true`** and **`false`** when both are **`false`**.

The Boolean operators have lower precedence than relational operators, and within them, **`not`** has the highest precedence, followed by **`and`**, and then **`or`**, so

```
a < b or not c > d and e <= f
```

is equivalent to

```
(a < b) or ((not (c > d)) and (e <= f))
```

`and` and **`or`** are what is called "short-circuiting" operators, which means that if they can tell the result after determining the value of their first operand, they don't bother evaluating the second one. Concretely, if **`X and Y`** determines that **`X`** is **`false`**, the whole expression is **`false`**, and **`Y`** is not evaluated. Similarly, if **`X or Y`** determines that **`X`** is **`true`**, the whole expression is **`true`**, and **`Y`** is not evaluated. This means that the first argument can be used as a "guard" in front of a second argument that may be expensive to compute or that may not be well-defined or will crash if the guard fails.

The clock

The `time` type refers to wall-clock time, but there's another notion of time that's often important in DMF systems. The board has its own internal clock, ticking away at some rate, and that rate determines the speed at which pads turn on and off and, therefore, the speed at which drops move. The clock can be referred to in DML as `the clock` or `the board's clock`, and there are several things you can do with it.

Pausing and resuming the clock

If you say `pause the clock` (or `pause clock`), the clock will be paused and no drop movement or state change will happen until it is resumed. Any threads of control that are trying to move drops or change pad states will simply pause. Depending on the device, other things may also pause, but anything waiting for a particular wall-clock time will not.

To resume the clock, you can say `resume the clock` (or `restart the clock` or `start the clock` or any of these without `the`). Anything that is waiting on the clock will resume.

Checking clock state

To check whether the clock is running, you can use the `running` or `paused` properties, as in

```
if the clock is paused { … }
```

The clock's update interval/rate

The clock's `update interval` (or simply `interval`) is the nominal amount of time between one tick and the next. Its `update rate` (or simply `rate`) is the same value viewed as a `frequency`. The clock's behavior can be changed by assigning new values to either of them. Note that the clock does not have to be running in order to be able to see or modify these values.

Ticks

It can occasionally be useful to be able to pause a computation for a number of ticks of the clock, taking into account pauses of the clock itself. To allow that, there is a `ticks` type and a unit of the same name, so you can say

```
wait for 3 ticks;
```

(`tick` is also a unit, so you can say `1 tick`.)

Note that unlike with `time`, the magnitude of a `ticks` value has to be an `integer`. If `t` is a value of type `ticks`, then `t's magnitude` gives you the number of ticks as an `integer`.

Delays

If you want to write a function or declare a variable that is only going to be used to control the length of time to wait for something, you can use the **`delay`** type, which can be either a **`time`** or a **`ticks`**. Most of the descriptions in the tutorial example of expressions that result in pauses, which were described as taking **`time`**, are actually defined in terms of **`delay`** and accept **`ticks`** as well.

Reagents

The `unknown` reagent

In addition to the **`waste`** reagent and reagents specified by **`reagent "Name"`**, there is one other built-in **`reagent`** value, specifiable as **`the unknown reagent`** (or **`unknown reagent`** or **`unknown`**). This is the value of **`w's reagent`** for any **`well w`** that hasn't otherwise been told what's in it. If you ask for a well to fill and it hasn't already held liquid, and you don't say what it is, that's the reagent you'll get, at least as far as the system's model is concerned. This is also the initial value of **`the interactive reagent`**, discussed below.

Creating reagents using `mixture`.

As discussed above, if **`A`** and **`B`** are reagents, you can say **`A+B`** to get a new **`reagent`** that's one part **`A`** and one part **`B`**. This generalizes to **`k*A + n*B`** to get a **`reagent`** that's **`k`** parts **`A`** plus **`n`** parts **`B`**. If, however, you say, **`A+B+C`**, you will likely be surprised to find that what you get is a reagent that describes itself as **`1 A + 1 B + 2 C`**. This occurs because **`A+B+C`** is actually interpreted as **`(A+B)+C`**, and if you mix a drop that's one part **`A`** and one part **`B`** with a drop that's all **`C`**, you'll get a mixture that has twice as much **`C`** as either **`A`** or **`B`**.

If you actually want to have an equal mixture of all three reagents, what you need to say is

```
r = mixture(A, B, C)
```

`mixture`, which takes up to eight arguments, mixes all of its arguments in the proportions given, so if you say

```
r = mixture(2*A, B, 3*C)
```

what you'll see when you print **`r`** is **`2 A + 1 B + 3 C`**.

Reagent names

If **`r`** is a **`reagent`**, **`r's`** name is a **`string`**. This will be either the **`string`** passed into the **`reagent expression`**, e.g. **`A`** for **`reagent "A"`** or it will be a description of the components of a mixture, like **`1 A + 2 B`**.

Using DML interactively

Some systems, e.g., Thylacine, allow the user to interact with the board "manually", presenting a GUI representation of the status of the board (including what drops are where and what's in each well) and allowing the user to change the state of pads by clicking and to execute DML statements by typing them. DML has some extra facilities that are useful for this use case. Note that these may not be available if DML is not being used interactively.

Syntactic changes for interactive commands

When issuing commands interactively, the semicolons that are typically required at the ends of statements become optional.

Also, if you declare a variable without giving its type, the system will behave as if you had specified **`local`** and use the type of the initializing expression, so you can simply type

```
        nsamples = 10
```

without the semicolon or the leading **`int`**.[23] Be careful, however, because if you later try to modify this variable, but misspell it, typing

```
        nsampels = 5
```

`nsamples` will retain its value of 10, and a new variable, **`nsampels`** will be created.[24]

Clicked pads and drops

If the system allows the user to click on a pad, either to identify it or to change its state, a DML program can identify the last clicked pad as **`the last clicked pad`** (or **`last clicked pad`** or **`clicked pad`**), which returns a **`(maybe) pad`**.

Similarly, **`the last clicked drop`** (or …) is a **`(maybe) drop`** which is the **`drop`** associated with **`last clicked pad`**. Note that if the drop has moved, **`last clicked pad`** will no longer return a value, since **`last clicked pad`** no longer has a drop.

Interactive reagents and volumes

When you manually tell the system that there is a drop someplace its model doesn't think there is one (on Thylacine by shift-clicking), the reagent that the system assumes is stored in the variable

[23] This lack of a requirement to specify the type also applies at the top level of files.
[24] This is, arguably, a design flaw.

`the interactive reagent` (or **`interactive reagent`**), which defaults to **`unknown`**. This is also the **`reagent`** that is assumed when you say

```
          ep = transfer in(0.5 uL);
```

specifying a **`volume`** rather than a **`liquid`**. You can, of course, change the value by saying

```
          interactive reagent = my_reagent;
```

Similarly, when you click to add liquid to or remove liquid from a pad, the system needs to know what the **`volume`** of that transfer is. This is stored in **`the interactive volume`** (or **`interactive volume`**), and the initial value is **`1 drop`**, the natural drop size the board dispenses. If you are manually transferring liquid in and out, it may be worth setting this to the volume you tend to transfer.

Resetting the board

At times, especially when interacting with the board manually, there may come times in which you need to reset the board to a known state. DML provides several **`reset`** actions that do this:

- **`reset pads`** turns off all pads and well pads (including well gates).
- **`reset heaters`** (or **`reset heating zones`**) turns off all heaters.
- **`reset chillers`** turns off all chillers.
- **`reset magnets`** turns off all magnets.
- **`reset all`** turns off all of the above, as well as all other components (e.g., fans, power supplies, sensors, and the like). Or, rather, it tells them to reset themselves, which may or may not do anything.

Pads

Most of what you can do with **`pad`**s has already been discussed. They are created by coordinate expressions:

```
          pad p = (5, 4);
```

or by attributes on other objects:

```
          pad p = well #1's exit pad;
```

You can also add a **`delta`** or **`direction`** to find the **`pad`**'s neighbors:

```
        pad p2 = p + 2 west;
```

Pads are **`binary components`**, so you can say

```
        p : on
        p : turn off
        p : toggle state.
```

You can get access to a pad's **`column`** (or **`col`** or **`x coordinate`** or **`x coord`**) and its **`row`** (or **`y coordinate`** or **`y coord`**). Pads also have attributes that allow you to get access to other components associated with them. This includes **`drop`**, **`well`**, **`heater`** (or **`heating zone`**), **`chiller`**, and **`extraction port`** (or **`extraction point`** or **`hole`**). These all return **`(maybe)`** values, so you can say

```
        if p doesn't have a drop { … }
        if p's heater exists { … }
```

Wells

Internal well structure

Within each **`well`** there is a **`well gate`** (next to the well's **`exit pad`**, which is a normal **`pad`** on the board proper) and a number of internal **`well pads`**. The model for each board defines sequences for turning these on and off in order to dispense drops, to absorb them from the exit pad, and to get the well into a state to transfer fluid into and out of the well from a pipettor. If all is going well, you should be able to simply use the high-level constructs provided by DML for doing these operations, but for those experimenting with new boards or trying to come up with new sequences, it is sometimes useful to turn these on and off directly.

To access the well's **`gate`**, you can simply use **`w's gate`**. To access an internal **`well pad`**, use

```
        well pad wp = w[4];
```

The mapping of **`integer`** to **`well pad`** will depend on the board. The **`well pad`** class includes both **`well gate`**s and internal **`well pad`**s. All have a **`well`** attribute, which identifies the well they're in, and all have a **`number`**. In the case of gates, the number will be **`-1`**.

Putting liquid in wells

The cleanest way to get liquid into wells is by using **`require`**, which is described above. This ensures that you have the quantity that you will need and allows you to give yourself a margin to avoid transferring too often.

For finer control, you can say

```
w : transfer in(20 uL of buffer);
```

or

```
w : transfer in(2.5 uL);
```

to add the same **`reagent`** that the well already contains. For the first form, if you give a reagent as a second argument:

```
w : transfer in(10 drops of X, my_product);
```

after the **`10 drops of X`** have been transferred in, the **`well's reagent`** is changed to be **`my_product`**. This can be useful when doing mixing within wells. When the mixture is complete, you can name the result rather than dealing with the components.

Another way to put liquid into a well is to say

```
w : fill;
w : fill(R);
```

These forms both **`transfer in`** reagent until the **`volume`** within the well reaches the well's **`fill level`**, which defaults to its **`capacity`**, but which can be assigned. In the former case, the **`reagent`** used is the well's current **`reagent`**, which defaults to **`unknown`**.

If you try to dispense a drop from a well where doing so will take it below the well's **`refill level`**, which defaults to **`0uL`**, **`fill`** will be called automatically.

Automatic refills

As an alternative to **`require`**, you can say

```
w : prepare to dispense 50 drops of reagent R;
```

This gives you less control over when the pipettor will be asked to transfer fluid (with **`require`** it happens then or not at all), but it can be useful when the amount of reagent you will need is more than the well can handle. This causes the well to fill itself to its **`fill level`** whenever it gets down to its **`refill level`**, except if it doesn't think it's going to need that much reagent for the rest of the run, in which case it only adds what it will need.

`prepare to dispense` can take a **`liquid`**, as shown above or it can take a **`volume`**, with the **`reagent`** defaulting to **`w's reagent`**. Alternatively, it can take a **`reagent`** or no argument. In those cases, the **`volume`** used is **`w's requirement`**, a **`(maybe) volume`**. If this is **`missing`** (the default), …[25] **`w's requirement`** is updated every time a drop is dispensed, so it will give you an estimate of how much will need to be dispensed before the run is over. If you change your mind partway through, you can assign it a new value, either greater or smaller.

Taking liquid out of wells

To remove liquid from a **`well`**, you can say

```
w : transfer out 20uL;
w : transfer out;
```

DML does not yet have any model of what happens off of the board, so what the pipettor does with the transferred liquid is up to it. In the second form, the well's entire **`volume`** is transferred.

You can also say

```
w : empty;
```

This transfers out liquid until the **`well`** gets down to its **`refill level`**.

If you try to add a drop to a well past a certain point (not yet visible in DML), **`empty`** will be called automatically.

Well attributes

The full list of attributes for a **`well`**, all of which have been described elsewhere, I believe is: **`gate`**, **`exit pad`**, **`exit dir`** (or **`exit direction`**), **`number`**, **`volume`**, **`reagent`**, **`contents`**, **`capacity`**, **`remaining capacity`**, **`requirement`**, **`fill level`**, **`refill level`**, **`heater`**, and **`chiller`**.

Other stuff

String forms

To turn any object into a **`string`**, you can say **`str(x)`**.[26] This is less needed than it used to be now that you can use the **`+`** operator with a **`string`** to do concatenation.

```
the drop's pad+"."
```

[25] It would take a fair bit of reading the code to figure out what happens here. It's not as straightforward as I had though. My quick reading is that this should be safe to use, but you probably shouldn't do it without specifying a **`volume`** or **`liquid`**, and if you use it, you probably shouldn't set **`w's fill level`** directly.
[26] If the format is ugly, that means I missed a case, and that should be fixed.

To concatenate an object's representation with a string. Note that if **`s`** is itself a **`string`**, **`str(s)`** will include quotation marks and possibly escape sequences, but when it is concatenated with another object, only the characters in the string are used.

Unsafe drop movement

On a DMF board, a **`drop`** is moved to an adjacent pad by turning on the pad it wants to move to and turning off the pad it is currently on, with both action scheduled to happen on the next clock tick. If two drops wind up on adjacent pads, it is quite likely that they will merge, and so to avoid such merging happening accidentally, the underlying Thylacine system enforces that a drop is only allowed to move to the next pad in its path if it is guaranteed that on neither this clock tick nor the next will there be any drops (other than itself) on either the pad it wants to move to nor any of its eight neighbor pads. It does this by requiring that the drop *reserve* these pads before scheduling the change in pad state. If there is another drop already on one of those pads, it will have to wait until that drop moves. Similarly, if another drop has already reserved one of the pads, indicating its own motion, this drop will wait until the other drop has passed.

The occasional deadlock aside, this typically works well to move drops from one part of the board to another, but it makes it impossible to intentionally walk drops together such that they will merge. This was a much bigger problem back before **`accept merge`**, **`merge into`**, and **`mix with`** were added to the language, as it made merging drops very difficult, but there are still probably situations in which it will be desirable.

Consider that you have two drops, **`d1`** and **`d2`**, where **`d1`** is two pads above **`d2`**, and you'd like to merge them onto the pad between them. You can't simply say

```
[[
   d1 : down;
   d2 : up;
]]
```

because the two drops would sit there forever, each waiting for the other to get out of the way. You could do it directly by changing the pad states:

```
[[
   d1 : off;
   d2 : off;
   d1 + down : on;
]]
```

(taking advantage of the fact that a **`drop`** implicitly converts to its **`pad`**), but that requires the programmer to be thinking about how a DMF board works rather than about what they want to do with it. So what we do instead is add an **`unsafe_walk`** function that takes a **`delta`** as an argument and returns an injection target that the **`drop`** can use, essentially saying, "Walk this **`delta`**, but don't bother trying to reserve things first". With this, the programmer can simply say

```
[[
   d1 : unsafe_walk(down);
   d2 : unsafe_walk(up);
]]
```

This is, of course, unsafe, and should be used sparingly, if at all. In this case, with the **`merge`** operators, the appropriate way to get this behavior is to say

```
[[
   d1 : accept merge from down : down;
   d2 : merge into up;
]]
```

(the second **`down`** needed to get the resulting drop into the center square, since high-level merging winds up on the space of the **`accept`**-ing drop).

One other wrinkle with any of these forms is that with all but the last one, you have to do more work to get your hands on the resulting merged drop, typically figuring out the pad on which the resulting drop will be and asking it for its **`drop`**. With the merging syntax, you are guaranteed that the identity of the resulting drop will be the same as the one calling **`accept merge`**, in this case, **`d1`**. (And it will be the result of both **`accept merge`** and **`merge into`**, so you could assign it if you didn't already conveniently have it in a variable.)

Units

These are the units currently recognized by DML, including synonyms. Most of them come in both "symbol" form and "English" form, with the English form allowing both singular an plural and both American and British spelling. Adding new units is easy.

- For **`time`**:
  - **`ms`**, **`millisecond`**, **`milliseconds`**
  - **`s`**, **`sec`**, **`secs`**, **`second`**, **`seconds`**
  - **`min`**, **`mins`**, **`minute`**, **`minutes`**
  - **`hr`**, **`hrs`**, **`hour`**, **`hours`**
- For **`ticks`**:
  - **`tick`**, **`ticks`**
- For **`volume`**:

  - `uL`, `ul`, `microliter`, `microlitre`, `microliters`, `microlitres`
  - `mL`, `ml`, `milliliter`, `millilitre`, `milliliters`, `milliliters`
  - `drop`, `drops`
- For `voltage`:
  - `mV`, `millivolt`, `millivolts`
  - `V`, `volt`, `volts`
- For `frequency`:
  - `Hz`, `hz`, `hertz`
- For `temperature difference`:
  - `C`
  - `F`

CHAPTER FOUR: **Types in Detail**

There isn't going to be time to do this in detail but my plan is to add a chapter covering each of the types, including, for each

- What does it represent?
- What other types can it be converted to (e.g., you can use a `drop` as a `pad`, with the value being `p's pad`)?
- How do you get one?
    - What's the syntax for literals?
    - `well #1`, `w's gate`, etc.
- What operators does it participate in and what is the result type?
- What attributes does it have? What are their types? What do they mean?
- What properties does it have? What do they mean?
    - `p is on`, `the clock is running`, `h is ready`.
- What injection targets expect it?