Noisy Language Reference, Draft Version 0.4

Phillip Stanley-Marbell
phillip.stanley-marbell@eng.cam.ac.uk

University of Cambridge,
Department of Engineering,
Cambridge, CB3 0FA.

Sensor-driven hardware platforms require appropriate programming abstractions. Native language constructs for abstractions relevant to a given domain allow compilers to reason about the semantics of programs for that domain and to thereby implement program transformations that improve safety, improve efficiency, or verify soundness. Noisy is a language designed for programming in the domain of sensor-driven hardware platforms such as the Warp platform. Noisy's facilities targeted at sensor-driven systems include primitives for physical signals with units of measure, primitives for accessing information on signal measurement uncertainty, operations for signal measurement through a CSP-like channel interface, primitives for program-directed sampling and quantization, and language-level primitives on continuous-time measurements and discrete-time (sampled) time-series data. A second language, Newton, complements the facilities and is intended for use by the designers of hardware platforms as opposed to those who program platforms using Noisy. Newton allows hardware designers to describe, physical properties of the hardware platform including the available sensors and the signals they generate, invariants or constraints between those signals dictated by both the electronics and mechanics of a sensor-enhanced system, and noise properties of the sensors characterized by a system's designer, and more. This document describes the motivation and design of Noisy and provides examples of its use.

Contents

DRAFT July 16, 2018-16:51

1. INTRODUCTION

Platforms driven by sensors are an important computing domain. These platforms range from wearable health-tracking devices, to home or office monitoring devices, to consumer and commercial robots, to unmanned aerial vehicles or drones. These platforms, which are referred to under different names including *cyberphysical* systems, *embedded* systems, or *Internet-of-Things* platforms, have a common property: Their software processes data from physical world interfaces such as temperature sensors, accelerometers, humidity sensors, or global positioning system (GPS) modules, and they may modify their environments through actuators such as motors or relays, or interact with users through displays.

Today, in order to be able to interact with hardware, which typically occurs through memory-mapped I/O to microcontroller peripherals such as I2C [48] or SPI [47], most of the software for embedded platforms is written

DRAFT -- DRAFT -- DRAFT -- DRAFT -- DRAFT -

in a combination of C and assembly language. Higher-level control and logic for these platforms is typically also written in C or C++, or may be written in stripped down versions of languages such as Python (MicroPython) [9] or JavaScript (JerryScript) [39]. To help bridge the gap between facilities provided in traditional programming languages, runtime systems, and the specific constraints of sensor-driven systems, several commercial and research languages have explored limited support for sensor-driven systems. This support has included adding units of measure or fundamental and derived dimensional quantities to augment program variable types and checking these at compile and runtime [35; 11; 5; 18; 6; 51; 43; 61; 20; 28; 29; 7; 41; 42].

Today, no existing programming languages, libraries, or runtime systems for sensor-driven systems provide language constructs or standard libraries to purposefully exploit restrictions caused by the laws of physics on the properties of the signals they process. Existing languages provide no mechanisms to ease the implementation of important tasks such as filtering time-series data, sensor fusion for combining the data from multiple sensors, or exploiting correlations between sensors mounted in a known physical configuration to obtain better accuracy, lower noise, or lower energy usage. And, existing languages and runtime systems do not provide constructs to assist programmers in modeling important concepts such as measurement uncertainty or significant figures. There is therefore an unmet need for software libraries, new programming constructs, or new programming languages where appropriate, to allow programmers to more easily deal with measurement data from the physical world, which is inherently noisy.

1.1 Libraries versus new programming languages

The capabilities described above could in principle be implemented using appropriate software libraries or `pragma` statements for existing embedded system programming languages such as C. Native or built-in language constructs allow a programmer to more succinctly describe and notate facilities such as per-variable significant figures, channels, latency, erasure, and error constraints on variables, and so on. At the same time, making these constructs part of a language exposes semantic information to the compiler that a compiler could otherwise not determine. This in turn enables compile-time transformations that exploit this semantic information. For example, language-level constructs for denoting units of measure allow a compiler to verify dimensional consistency of arithmetic operations, at compile-time. A library interface on the other hand could only validate such consistency at runtime and would likely require much more work from the programmer in the form of using an application programming interface (API) for all arithmetic. Language-level abstractions also allow us to present the techniques which exploit information from various constructs more succinctly. We therefore choose to explore the new constructs we propose as a new domain-specific language. For wider deployment beyond our research goals, where the adoption of a new programming language might be a significant barrier, some of the techniques in Noisy could be provided as libraries, however cumbersome, for host languages such as C.

1.2 Noisy

Noisy is a language for processing signals from the physical world and for exploiting knowledge about correlations between signals or invariants obeyed by signals, to make the task of programming easier, to enable new types of compile-time program transformations based on physics, and to make programs more efficient. The design motivations for Noisy are:

(1) **Coupling physical signals to program variables:** To allow programmers to denote the physical signals associated with program variables.

(2) **Coupling physical signals to invariants and physical laws:** To allow the compilers and runtime system to exploit coupling between signals through invariants (laws) relating signals specified in the Newton [45] language.

(3) **Basic data types for signal processing:** To ease the work of programmers implementing computations on values from sensors by providing native datatypes for time series, vectors, sets, and operators that ease the computation on these physical types such as computing the frequency modes of time series data, integrating, and differentiating time series data.

DRAFT -- DRAFT -- DRAFT -- DRAFT -- DRAFT -

(4) **Measurement uncertainty:** To allow programs to determine the uncertainty of values of variables representing signals as they are read directly from sensors or after subsequent computing on them.

(5) **Tolerable result uncertainty:** To allow programs to specify precision, accuracy, reliability, significant figures, latency tolerance constraints, and constraint violation control flow.

(6) **Program transformations exploiting signal correlations, physics, and uncertainty:** To incorporate an appropriate set of facilities into the language to enable compilers to extract semantic information necessary to enable new program transformations relevant to sensor-driven systems.

Noisy is intended to be an implementation platform to investigate a number of research questions. The specific research aims include:

—**Substituting sensors in computations based on physical correlations:** To evaluate whether sensor substitution is a viable technique for either improving the accuracy of sensing algorithms or for reducing the energy usage of sensor driven programs while maintaining their functionality. Information provided by the **`signal`**, **`epsilon`**, and **`sigfigs`** type annotation in Noisy makes this possible.

—**Automating opportunities for reducing sensor accuracy:** To evaluate whether tracking measurement uncertainty can provide automated opportunities for purposefully inducing measurement uncertainty for sensor interactions in exchange for lower sensor power dissipation, and to quantify how much benefit can be gained from doing so for realistic programs. Information from the **`epsilon`** and **`sigfigs`** type annotation in Noisy makes this possible.

—**Safety of sensor-driven programs:** To evaluate whether tracking measurement uncertainty in programs can make programs safer. Our goal is to evaluate the effect of significant figure tracking on program safety both by quantitatively evaluating the effect of compiler feedback enabled by language-level significant figure tracking, as well as safety enabled by program transformations and compile-time analysis guided by language-level significant figure annotation. One measure of program safety will be whether our proposed techniques allow us to identify or repair errors in example programs known to have defects. The **`uncertainty`** operator, which gives the posterior probability distribution for a variable of **`signal`** type, together with the **`centralmoment`** operator which computes the nth central moment of the distribution, make this possible.

—**Implementation efficiency of significant-figure tracking:** To evaluate whether runtime systems can track measurement uncertainty in programs efficiently.

—**Utility and overhead of signal processing types:** To evaluate the utility of language-level support for signal processing such as representing time series and operators on time series, and to quantify the performance benefit that these facilities can provide by exploiting hardware opportunities for signal processing acceleration.

—**Reducing information leakage in digital and analog sensors:** The sensor signal specifications of tolerable errors, erasures, and latency distributions (the **`sigfigs`**, **`epsilon`**, **`alpha`**, and **`tau`** constructs) allow programs to specify tolerable inaccuracy, tolerable unreliability, and tolerable jitter on sensing operations. This information can be used to enable new approaches to improving sensor hardware privacy by filtering, reducing precision, and inducing jitter in the signals produced by sensors so that those signals remain usable by a given legitimate application but cannot be co-opted by malicious applications.

Figure 1 shows how Noisy programs are combined with a Newton platform description and low-level device interface code and compiled to executables for a given platform.

1.3 Signals and physics in Noisy

Noisy introduces the concept of *signal designations*. Any numeric type in Noisy can be designated to be one of seven base dimensions corresponding to the seven base SI units, one of five base signals (derived dimensions) (**`pressure`**, **`acceleration`**, **`magneticflux`**, **`humidity`**, **`anglerate`**), or one of the additional signals defined in a platform's Newton description. Figure 2 shows an example of a declaration of a numeric variable of type **`int`** with a signal designation of **`pressure`**. Noisy's semantics requires variables with signal designations to be used in *dimensionally-consistent* ways: addition, subtraction and comparisons of variables with different signal designations are not well-typed.

DRAFT -- DRAFT -- DRAFT -- DRAFT -- DRAFT -

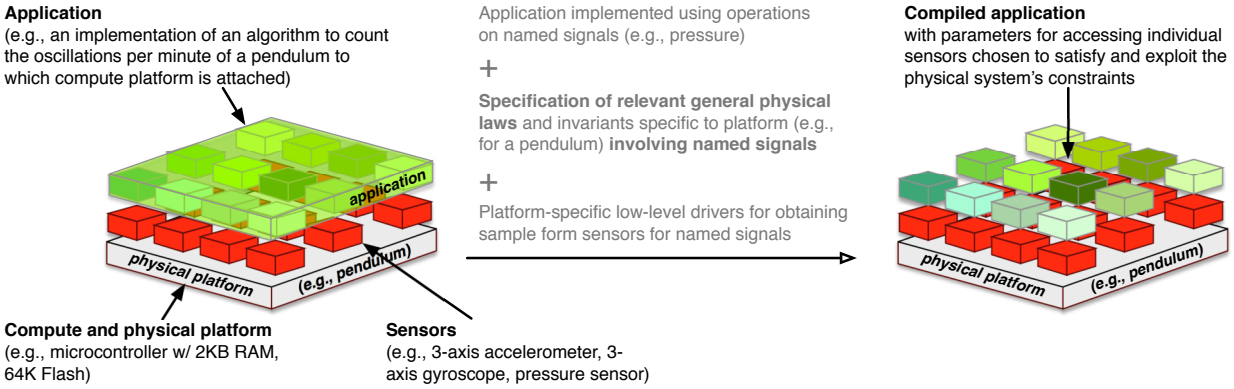


Fig. 1. Programs written in Noisy specify interaction with sensors in terms of signal types such as **`pressure`** or **`temperature`**. Hardware system designers provide physical platform descriptions written in Newton which specify general physical laws relevant to the physical system as well as specific invariants satisfied by a given physical system. Along with low-level device interface code for retrieving samples from sensors, the Noisy program is compiled to executables for a given platform. The transformations applied to the Noisy program are enabled by the information exposed in the Newton platform description.

```
p1 : int16 and signal pressure;
```

Fig. 2. Numeric types in Noisy can include an optional signal designation.

Noisy's semantics treats numeric types with signal designations as obeying any invariants specified in a platform's Newton description. This allows a Noisy compiler to use the invariants specified in a platform's Newton description to perform program transformations that satisfy those invariants but which may improve program performance or efficiency.

To read sensor values for a given signal type, programs declare *channels* with the type of the desired signal, and read from those channels. Reads from signal channels not supported on a given platform fail, returning the value **`nil`**, in much the same way that memory allocation in languages with dynamic memory allocation will fail if the platform does not have sufficient memory.

```
h                    : int16 and dimensions distance;
p2                   : int16 and signal pressure and units (1/1000) * kilogram * meter**(-1) * second**(-2);
seaLevelPressure     : const 101325 and units kilogram * meter**(-1) * second**(-2);
```

Fig. 3. Numeric types in Noisy can include an optional signal designation.

1.4 Dimensions and units of measure in Noisy

Variables with signal designations implicitly acquire the signal's SI units of measure. For example, the variable **`p1`** in Figure 2 has implicit units $\text{kilogram} \cdot \text{meter}^{-1} \cdot \text{second}^{-2}$. Figure 3 shows how variables and constants may also be assigned explicit dimensions and units of measure. For example, in Figure 3, the variable **`h`** is declared with explicit dimensions of distance. The variables **`p2`** and **`seaLevelPressure`** both have the same dimensions ($\text{mass} \cdot \text{length}^{-1} \cdot \text{time}^{-2}$) but have different units or measure. The variable **`p2`** and the variable **`seaLevelPressure`** have different units of measure (units **`(1/1000) kilogram meter**(-1) second**(-2)`** or milli Pascals for **`p2`**, in contrast to units **`kilogram * meter**(-1) * second**(-2)`** or Pascals for **`seaLevelPressure`**).

Values without explicit or implicit units of measure are unitless. Noisy's semantics requires all expressions in comparisons, addition, subtraction and assignment to be of the same units of measure.

Subroutines in Noisy may be parametrized on dimensions. Figure 4 shows a subroutine, **`square`**, which takes a value **`integerArgument`** as argument and a dimension parameter **`dimensionParameter`** and returns a result **`resultValue`** with dimensions **`dimensionParameter**2`**.

DRAFT -- DRAFT -- DRAFT -- DRAFT -- DRAFT -

```
square : function (integerArgument: int32 and dimensionParameter: dimparam) -> (resultValue: int32 and dimensions dimensionParameter**2)
{
        return (resultValue: integerArgument*integerArgument);
}
```

Fig. 4. Numeric types in Noisy can include an optional signal designation.

```
pressureSamples : int32 and signal pressure and timeseries;
gyroSamples     : int32 and signal anglerate and timeseries;

gyroSamples     =<- [kSampleCount] signal anglerate;
pressureSamples =<- [kSampleCount] signal pressure;
```

Fig. 5. Time series in Noisy simplify processing sensor signals.

1.5 Time series of signals in Noisy

Values read from sensors are often time series of readings sampled at a known rate. Noisy allows programmers to define variables as time series using the **`timeseries`** designator. Reads from channels can specify a number of samples to read into a time series variable. Figure 5 illustrates with an example. Noisy provides several operators for operating on time series data, such as for obtaining the list of frequency and amplitude tuples of the modes of oscillation in a signal (**`fourier`**), integration over time and differentiation with respect to time (**`tintegrate`** and **`tdifferentiate`**), and obtaining a list of the time stamps or samples for a given time series (**`timebase`** and **`samples`**) as well as constructors for creating time series from a list or array of numeric values (**`timeseries`**).

1.6 Notating and computing with timing uncertainty and measurement value uncertainty in Noisy

All physical measurements have limited precision and as a result, all signal sample values have a limited number of significant figures. As values are used in the arithmetic operations of signal processing algorithms and combined through arithmetic with constants and with other signal sample values, the uncertainty in the individual bits of their value representations may degrade further. Existing languages provide no way to determine the amount of measurement uncertainty associated with values obtained from sensors. Recent work [13] provides one mechanism for tracking measurement uncertainty once values are obtained from sensors by keeping track of the entire probability distribution of values and using Bayesian networks constructed based on a program's dataflow, to compute new probability distributions for each step of a computation. Such methods of algebra on arbitrarily-distributed random variables is seductive, but is only possible for a limited number of types of distributions and arithmetic operations.

```
seaLevelPressure        : const 101325 and units kilogram * meter**(-1) * second**(-2);
approximatePressure     : int32 and signal pressure and sigfigs 10;

gyroSample              :=<- signal anglerate;

#
#       The sigfigs operator returns the number of significant figures
#       of its operand.
#
if (sigfigs gyroSample == sigfigs seaLevelPressure)
{
}
else if (sigfigs gyroSample == sigfigs approximatePressure)
{
}
```

Fig. 6. Noisy makes it easier for programmers to write safer software that processes signals from the physical world. It allows programmers to specify the number of significant figures to be maintained for variables, and by providing constructs to determine the number of significant figures in signal samples obtained from sensors.

DRAFT -- DRAFT -- DRAFT -- DRAFT -- DRAFT -

Noisy provides programmer support for reasoning about value uncertainty in sample values of signals as well as any numeric program value using three techniques: Static source-level annotation of significant figures for constant and variables, support for a dynamic runtime semantics which optionally tracks the number of significant figures for every program value when there is hardware support to do so, and support for dynamic runtime determination of significant figures for any value in a Noisy program. Figure 6 illustrates how Noisy programs can specify the significant figures in a constant, or can determine the number of significant figures in a value obtained at runtime from a sensor signal. The syntactic constructs for source-level annotation of significant figures and the semantics of Noisy's significant figure constructs are described later in this document.

In addition to specifying the number of significant figures that are meaningful for a given program variable, programmers may wish to specify that they are willing to permit values of specific program variables to take on a given distribution of random errors at runtime.

We refer to the difference between the correct and erroneous values as the *error magnitude*. An error magnitude tolerance specifies the acceptable distribution on the error magnitude values. For example, a plain English specification of a simple error tolerance constraint could be "Ensure that the error magnitude only exceeds 2.0 at most one out of every million times that a value is read". If the error magnitude is denoted by a random variable M, the above statement could be written more precisely as

$$\Pr\{M > 2.0\} \quad \leq \quad \frac{1}{1,000,000}$$

When channels in Noisy act as the interface to sensors, reads from a channel may fail due to communication failures with a sensor [59]. Such loss will be referred to as *channel-level erasures*. A channel erasure tolerance constraint thus specifies the acceptable distribution on the *loss fraction* of values.

Because operations on channels, can have non-deterministic latencies, since they depend on the state of the underlying communication interconnect, a *latency tolerance constraint* enables a Noisy program to specify how much latency on a communication is acceptable. The syntactic notation for these error-tolerance specifications are described later in this document.

Error tolerance specifications allow the Noisy compiler to perform two kinds of transformations. First, given an error-tolerance specification, the Noisy compiler can statically at compile time deduce the implied number of significant figures, and this can be queried by programs dynamically at runtime as described above. Second, given an error-tolerance specification on a channel variable, the Noisy compiler can use allow samples to be elided at runtime, or sample values to be encoded using techniques such as value-deviation-bounded serial (VDBS) encoding [60; 57] to reduce sensor I/O energy costs. Noisy's error-tolerance specification constructs are described later in this document.

1.7 Organization of Noisy applications

Programs in Noisy are organized into units called *functions* within a *module*. Functions are collections of program statements (e.g., like functions or procedures in Algol family languages). Functions in Noisy can also be treated as channels, so function calls can be written alternatively as explicit communication rather than transfer of control flow.

2. EXAMPLES

The following examples highlight Noisy's basic syntax (Section 2.1), its concepts of physical signals (Section 2.2), and its concept of problem definitions (Section 6.9).

2.1 Hello, World

The example below prints the string "Hello, World!" on the standard output:

```
include "system.nd"

#
#       The module definition gives its signature for other
#       modules (e.g., the runtime system) that want to execute
#       it.
```

DRAFT -- DRAFT -- DRAFT -- DRAFT -- DRAFT -

```
#
#       The module definition need not export the function init
#       if it is not intended to by loaded by the "conventional loader"
#       (e.g., the OS shell).
#
HelloWorld : module
{
        init    : function (args: list of string) -> (results: list of string);
}

init : function (arguments: list of string) -> (results: list of string) =
{
        utf8BytesPrinted : int64;

        #
        #       The first argument to the ‘load‘ operator is the
        #       type of the channel that will be created. The recommended
        #       way to specify this in the case of a function implementation
        #       which is being loaded, is to use the ‘typeof‘ operator to
        #       get the type specified in the function’s progtype.
        #
        #       In this case, ‘typeof System.print‘ is the type expression
        #       ‘list of string‘.
        #
        print := load (typeof System->print) (path System->print);

        #
        #       Functions in Noisy are shorthand for channels. We can
        #       call the ‘print‘ function in the System module using
        #       C-style function notation, in which case the semantics
        #       are that the statement completes
        #
        utf8BytesPrinted = print("Hello World!"::nil);

        #
        #       We can also treat the ‘print‘ function as a channel, in
        #       which case we can separate the delivery of its arguments
        #       from the reception of the results. This creates a new
        #       process/thread that remains alive as long as the channel
        #       is not nil.
        #
        #       Send a value with type ‘list of string‘ down the channel.
        #
        print <-= "Hello World!"::nil;

        #
        #       The read type of the channel, as defined in system.nd
        #       is int64. The semantics are that the read gives the
        #       number of UTF-8 bytes of the last formatting. We can
        #       therefore read this ‘print‘ channel to get the equivalent
        #       of the "return value" of the last print.
        #
        utf8BytesPrinted = <- print;

        #
        #       As long as the ‘print‘ channel is valid (i.e., in scope
        #       and not nil), the runtime system will keep it around.
        #       We can force the print co-routine’s demise by setting the
        #       channel to nil. (Going out of scope at the function’s end
        #       achieves the same, so this is not really necessary.)
```

DRAFT -- DRAFT -- DRAFT -- DRAFT -- DRAFT -

```
        #
        print = nil;
}
```

2.2 Pedometer

The listing below shows the module definition and specification of a pedometer application in Noisy.

```
#
#       The function 'computeSteps' takes a timeseries of samples and computes
#       the number of steps.
#
#       The function 'start' reads from the appropriate sensor and sends the
#       samples to computeSteps. The implementation of 'start' in pedometer.n
#       is a basic one which works from a single 1-axis sensor. In practice,
#       start would continuously monitor three axes of a 3-axis accelerometer
#       to determine which one has the maximum peak-to-peak deviation for each
#       time window and would send the samples from that axis to computeSteps.
#
pedometer : module(lengthType: type, sampleType: type, countType: type)
{
        computeStepsSamples     : function (inputSamples: sampleType and timeseries) -> (count: countType);
        computeStepsMeasurement : function (measurement: signal) -> (count: countType);
        sampler                 : function (measurement: signal, rate: countType) -> (sampleTimes: list of countType);
        start                   : function (windowSampleCount: lengthType) -> (stepsChannel: chan of countType);

        computeStepsSamples     : probdef (inputSamples: sampleType and timeseries) -> (count: countType);
        computeStepsMeasurement : probdef (measurement: signal) -> (count: countType);
        sampler                 : probdef (measurement: signal, rate: countType) -> (sampleTimes: list of countType);
        start                   : probdef (windowSampleCount: lengthType) -> (stepsChannel: chan of countType);

        init                    : function (arguments: list of string) -> (results: list of string);
}

#
#       Problem definition (probdef) for the computeSteps function.
#
#       A very simple invariant that does not even define the computational
#       problem: There cannot be more steps than there are window samples.
#
computeStepsSamples : probdef (inputSamples: sampleType and timeseries) -> (count: countType) =>
{
        #
        #       The 'timebase' operator applied to a time series yields
        #       a list of timestamps (in seconds).
        #
        given (windowTime == (head (sort (timebase inputSamples))) - (head (reverse (sort (timebase inputSamples)))))
        {
                (count < (length inputSamples))

                &&

                #
                #       The 'fourier' operator applied to a time series
                #       returns a list of pairs the freuencies in seconds of the
                #       component sinusoids and their amplitudes, ordered by decreasing amplitude
                #
                exists (cutoff in int8)
                {
                        head (head (fourier (lowpass inputSamples cutoff))) == (count / windowTime)
```

DRAFT -- DRAFT -- DRAFT -- DRAFT -- DRAFT -

```
                }
        }
}

#
#       A ‘signal‘ (like the variable ‘measurement‘) is a window of time of a continuous-time signal
#
computeStepsMeasurement : probdef (measurement: signal) -> (count: countType) =>
{
        #
        #       The ‘timebase‘ operator applied to a time series yields
        #       a list of timestamps (in seconds).
        #
        given (windowTime == (head (sort (timebase measurement))) - (head (reverse (sort (timebase measurement)))))
        {
                #
                #       The ‘fourier‘ operator applied to a time series
                #       returns a list of pairs of the freuencies in seconds of the
                #       component sinusoids and their amplitudes, ordered by decreasing amplitude
                #
                exists (cutoff in int8)
                {
                        head (head (fourier (lowpass measurement cutoff))) == (count / windowTime)
                }
        }
}

#
#       Problem definition (probdef) for the sampler function
#
sampler : probdef (measurement: signal, rate: countType) -> (sampleTimes: list of countType) =>
{
        #
        #       Specify tolerable sample rate deviation and tolerable jitter deviation
        #
}

#
#       Problem definition (probdef) for the start function
#
start : probdef (windowSampleCount: lengthType) -> (stepsChannel: chan of countType) =>
{
}
```

The listing below shows one module implementation the pedometer application in Noisy.

```
#
#       For the math->min and math->max function:
#
include "math.nd"
include "VDBS.nd"
include "pedometer.nd"

enum
{
        kPedometerSampleRate = 10,
        kPedometerLowpassCutoffFrequency = 20
};

#
#       For the definition of the definition of ’accelerometerTypeAnnote’,
```

DRAFT -- DRAFT -- DRAFT -- DRAFT -- DRAFT -

```
#       which is a sequence of epsilon/tau/alpha specifications which
#       specify the tolerable error, erasure, latency distribution/jitter.
#
include "sensorErrorTypes.nd"

#
#       Compute the number of steps taken in a given window of samples from
#       a single axis.
#
computeStepsSamples : function (inputSamples: sampleType and timeseries) -> (stepCount: countType) =
{
        windowMin, windowMax, windowMidPoint    : sampleType;
        stepCount                               : countType = 0;

        #
        #       Load the math module implementation (at the path determined by
        #       applying the ‘path‘ operator to the ‘Math‘ module type).
        #
        math := load Math (path Math);

        #
        #       Low-pass filter the timeseries data passed in, with
        #       a cutoff frequency of 20Hz
        #
        filteredSamples := lowpass inputSamples kPedometerLowpassCutoffFrequency;

        windowMin = typemax sampleType;
        windowMax = typemin sampleType;

        sequence (s in filteredSamples)
        {
                windowMin = math->min(a: windowMin, b: s);
                windowMax = math->max(a: windowMax, b: s);
        }

        windowMidPoint = (windowMin + windowMax)/2;
        stepCount = 0;
        sequence (i := 0; i < (length filteredSamples) - 1; i++)
        {
                if ((filteredSamples[i] > windowMidPoint) && (filteredSamples[i+1] < windowMidPoint))
                {
                        stepCount++;
                }
        }
}

#
#       Compute the number of steps taken in a given window of a non-sampled signal
#       measurment, from a single axis signal.
#
computeStepsMeasurement : function (measurement: signal) -> (count: countType) =
{
        windowMin, windowMax, windowMidPoint    : sampleType;
        stepCount                               : countType = 0;

        #
        #       Load the math module implementation (at the path determined by
        #       applying the ‘path‘ operator to the ‘Math‘ module type).
        #
        math := load Math (path Math);
```

DRAFT -- DRAFT -- DRAFT -- DRAFT -- DRAFT -

```
76
77          #
78          #       Load the VDBS module implementation (at the path determined by
79          #       applying the ‘path‘ operator to the ‘VDBS‘ module type).
80          #
81          vdbs := load VDBS (path VDBS);
82
83          #
84          #       Quantize the measurement with the VDBS quantizer from the VDBS module.
85          #       In practice, this will mean re-quantizing the signal to apply VDBS
86          #       encoding. A program analysis should in principle be able to determine
87          #       that the signal is only used quantized, and to ensure only the quantized
88          #       version is reuqested from a sensor. vdbs8bitM64Quantizer is a constant
89          #       expression defined in the VDBS module.
90          #
91          quantizedMeasurement := vdbs->vdbs8bitM64Quantizer(measurement);
92
93          #
94          #       Sample the signal at time offsets defined by the function sampler.
95          #       (defined below). The sampler could in principle be a non-uniform-time
96          #       sampler (i.e., with jitter) or even a non-uniform-rate sampler (i.e.,
97          #       not always returning the same number of sampling points per second).
98          #
99          quantizedAndSampledMeasurement := quantizedMeasurement sample sampler(measurement, kPedometerSampleRate);
100
101         #
102         #       Low-pass filter the timeseries data passed in, with
103         #       a cutoff frequency of 20Hz
104         #
105         filteredSamples := lowpass quantizedAndSampledMeasurement kPedometerLowpassCutoffFrequency;
106
107         windowMin = typemax(sampleType);
108         windowMax = typemin(sampleType);
109
110         sequence (s in filteredSamples)
111         {
112                 windowMin = math->min(a: windowMin, b: s);
113                 windowMax = math->max(a: windowMax, b: s);
114         }
115
116         windowMidPoint = (windowMin + windowMax)/2;
117         stepCount = 0;
118         sequence (i := 0; i < (length filteredSamples) - 1; i++)
119         {
120                 if ((filteredSamples[i] > windowMidPoint) && (filteredSamples[i+1] < windowMidPoint))
121                 {
122                         stepCount++;
123                 }
124         }
125
126         return (count: stepCount);
127 }
128
129 sampler : function (measurement: signal, rate: countType) -> (sampleTimes: list of countType)
130 {
131         times := nill;
132
133         sampleCount := rate * ((head (sort (timebase measurement))) - (head (reverse (sort (timebase measurement)))));
134         sequence (i := 0; i < sampleCount; i++)
135         {
```

DRAFT -- DRAFT -- DRAFT -- DRAFT -- DRAFT -

```
                times = i::times;
        }

        return (sampleTimes: times);
}

#
#       This simple driver for computeSteps only reads from a single sensor
#       signal (acceleration@0).
#
#       A more sophisticated implementation would read from all three axes
#       of a 3-axis accelerometer.
#
start : function (windowSampleCount: lengthType) -> (stepsChannel: chan of countType) =
{
        #
        #       Leave it up to the runtime to determine where to get the
        #       accelerometer samples from, how to configure the sensor
        #       based on the type annotation in accelerometerTypeAnnote, etc.
        #       These will come from a Newton 'sigsource' description.
        #
        accelerometer           : chan of sampleType and signal acceleration@0 and accelerometerTypeAnnote;
        accelerometerSamples    : sampleType and timeseries;

        sequence (;;)
        {
                #
                #       Compute steps by explicitly sampling from accelerometer signal
                #
                accelerometerSamples    =<- [windowSampleCount] accelerometer;
                stepsChannel            <-= computeStepsSamples(inputSamples: accelerometerSamples);

                #
                #       Compute steps by working directly on un-sampled signal (in practice, might mean re-sampling)
                #
                stepsChannel            <-= computeStepsSamples(measurement: <-accelerometer);
        }
}

init : function (arguments: list of string) -> (results: list of string) =
{
}
```

2.3 Sorting

The listing below shows the implementation and problem definition for sorting, implemented in Noisy.

```
include "sortList-variantA.nd"

SelectionSort : module(valueType: type)
{
        init    : function (args: list of string) -> (results: list of string);

        sorter  : function (inputList: list of valueType) -> (outputList: list of valueType);
        sorter  : probdef (inputList: list of valueType) -> (outputList: list of valueType);
}

init : function (args: list of string) -> (results: list of string) =
{
        return (results: sorter(tail args));
```

DRAFT -- DRAFT -- DRAFT -- DRAFT -- DRAFT -

```
}

sorter : function (inputList: list of valueType) : (outputList: list of valueType) =
{
        #
        #       Pre-conditions: The init function is created, and a valid
        #               list-of-string input is written to it.
        #
        #       Post-conditions: The reader of the init function reads a
        #               list of string whose head is the largest item,
        #               and the items are in non-increasing order from
        #               head to tail, lexicographically.
        #
        rest, result            : list of string;
        smallest                : string;

        sequence (rest = inputList; length rest > 0;)
        {
                #
                #       Loop invariants: 'result' list contains no items
                #               larger (lexicographically) than 'rest' list.
                #
                #       Progress: in each iteration, an item is removed
                #               from 'rest'
                #
                #       Termination: when 'rest' is empty.
                #
                ;
                (smallest, rest) = findSmallest(rest);
                result = smallest :: result;
        }

        return (outputList: result);
}

findSmallest : function (stringList: list of string) -> (result: (string, list of string)) =
{
        #
        #       Pre-conditions: The findSmallest function is created, and a
        #               valid list-of-string input is written to it.
        #
        #       Post-conditions: The reader of the findSmallest  function
        #               reads a tuple, first item of which is a string, no
        #               larger (lexicographically) than any item on the
        #               incoming list, and the second item in the tuple is a
        #               list of strings being the incoming list with one of
        #               the possible multiple copies of the lexicographically
        #               smallest item removed.
        #
        rest            : list of string;
        input           := stringList;
        smallest        := head input;

        sequence (; length input > 0;)
        {
                #
                #       Loop invariant: 'smallest' is the lexicographically
                #               smallest item seen on input thus far, and
                #               is no smaller than any item in 'rest'.
                #
```

DRAFT -- DRAFT -- DRAFT -- DRAFT -- DRAFT -

```
74              #       Progress: in each iteration, an item is removed from
75              #               'input'.
76              #
77              #       Termination: when input list is empty.
78              #
79              item := head input;
80              match
81              {
82                      item <= smallest =>
83                      {
84                              rest = smallest :: rest;
85                              smallest = item;
86                      }
87
88                      item > smallest =>
89                      {
90                              rest = item :: rest;
91                      }
92              }
93              input = tail input;
94      }
95
96      return (result: (smallest, rest));
97  }
```

DRAFT -- DRAFT -- DRAFT -- DRAFT -- DRAFT -

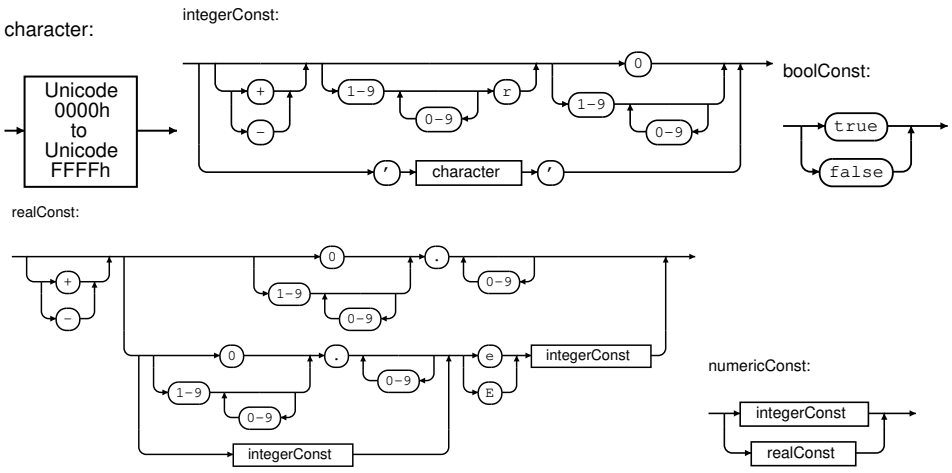


Fig. 7. Syntax diagrams for lexical elements (excluding reserved identifiers, operators, and separators which are detailed in Section 3.1).

3. LEXICAL ELEMENTS

Programs are sequences of Unicode [62] characters, organized according to the rules of the language grammar. Tokens are separated by whitespace, operators or other separators. Whitespace consists of `'\␣'`, `'\n'`, `'\r'` and `'\t'`. Separators and operators may abut one or more tokens. In addition to these separators and operators, several tokens are reserved for use in the language and have special meaning; they may not be used as identifiers. Comments are introduced with the character #, and continue until the next newline, or the end of input:

```
#       This is a comment
```

Noisy uses `#` as the comment character rather than other choices such as C-style comments `/* ... */` and `//` because using a single-token comment marker leads to simpler semantics for comments: Any character between the comment marker and the following newline is ignored. Because their semantics can be more complicated, such as when dealing with nested comments, multi-line comments such as those introduced with `/* ... */` can lead to incorrect demarcation of comments both in compilation as well as in editors. In particular, when there is a discrepancy between the semantics for a particular comment as determined by the compiler versus a programmer's text editor, such a discrepancy can be used by malicious programmers to obfuscate malware [46].

3.1 Reserved tokens

A set of single and multiple character tokens are lexically reserved and may not be used in identifiers. The reserved operators and separators are:

```
~       !       %       ^       &       *       (       )       -       +       =       /       >       <       ;
:       '       ""      {       }       [       ]       |       <-      .       ,       <=      >=      ^=      |=
&=      %=      /=      *=      -=      +=      :=      !=      >>      >>=     <<      <<=     &&      ||      ::
==      --      ++      <-=     =>      ->      ==@     **      >=<     #
```

The reserved identifiers in the language are:

```
acceleration            adt             alpha           ampere          anglerate       bool            candela
centralmoment           chan            const           crossproduct    current         dimensions      dimparam
distance                dotproduct      else            epsilon         erasures        errors          false
fixed                   float128        float16         float32         float4          float64         float8
fourier                 function        head            highpass        humidity        imaginary       int128
if                      int16           int32           int4            int64           int8            iter
kelvin                  kilogram        latency         length          list            lowpass         luminosity
magneticflux            mass            match           matchseq        material        meter           module
```

DRAFT -- DRAFT -- DRAFT -- DRAFT -- DRAFT -

```
mole            nat128          nat16           nat32           nat4            nat64           nat8
nil             of              predicate       pressure        rational        real            reverse
samples         second          set             sigfigs         signal          sort            string
tail            tau             tderivative     temperature     time            timebase        timeseries
tintegral       true            type            typeof          uncertainty     units           valfn
vector
```

The production rules employed in lexical analysis for determining the terminal symbols from sequences of Unicode characters, can be described by a *regular language* [4], whose productions are shown by the syntax diagrams in Figure 7.

4. SYNTACTIC ELEMENTS

A sequence of Unicode characters, which corresponds to a sequence of one or more tokens as described in the preceding section is a valid program if it conforms to the rules of the language grammar. A complete language grammar in EBNF [66] notation is provided in Appendix D.

4.1 Programs

A Noisy program is composed of a single program interface definition (*module definition*) and a collection of *functions*. Because the interface to functions can also be accessed using communication channel construct, channels in Noisy are sometimes referred to as *name generators*. The module definition specifies a set of constants, type declarations, and publicly-visible functions.

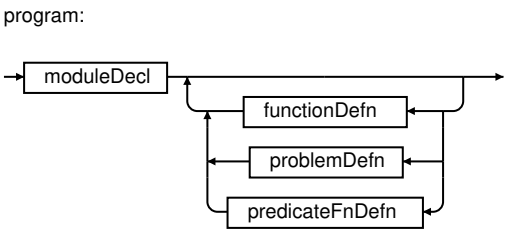


Fig. 8. Syntax diagram for the overall syntactic structure of Noisy programs.

Example:

```
1 Hello : module
2 {
3         init : function(nil) -> (nil);
4 };
```

4.2 Types, type expressions, and type declarations

Noisy is statically checked and strongly typed. Every expression can be assigned a unique type, and the compiler will not accept as valid any program for which a type error can occur at runtime. The syntax of the basic and derived types are represented by the syntax diagrams in Figure 11. The basic data types are **bool**, **nat4**, **nat8**, **nat16**, **nat32**, **nat64**, **nat128**, **string**, **int4**, **int8**, **int16**, **int32**, **int64**, **int128**, **float4**, **float8**, **float16**, **float32**, **float64**,**float128**, and **fixed**. A basic type may have associated with it one or more *error*, *loss* (i.e., erasure), or *latency* tolerance constraints as well as designators for *signals* and *significant figures*. Variables of type **bool** are 1-bit values, **nat**n are n-bit unsigned integers, **int**n are n are n-bit signed integers in two's complement format. Type **float**n are n-bit floating-point values. The type **fixed** is a fixed-point representation for real values.

Types can have *dimension designations* corresponding to one of the seven base SI units (**distance**, **mass**, **time**, **material**, **current**, **luminosity**, **temperature**). Types can have *units of measure designations* corresponding to one of the standard units for the seven base SI units (**meter**, **kilogram**, **second**, **mole**, **ampere**, **candela**, **kelvin**). Types can have *signal designations*. Any numeric type can be designated by a program to be one of seven base signals corresponding to the seven base SI units (**distance**, **mass**, **time**, **material**,

DRAFT -- DRAFT -- DRAFT -- DRAFT -- DRAFT -

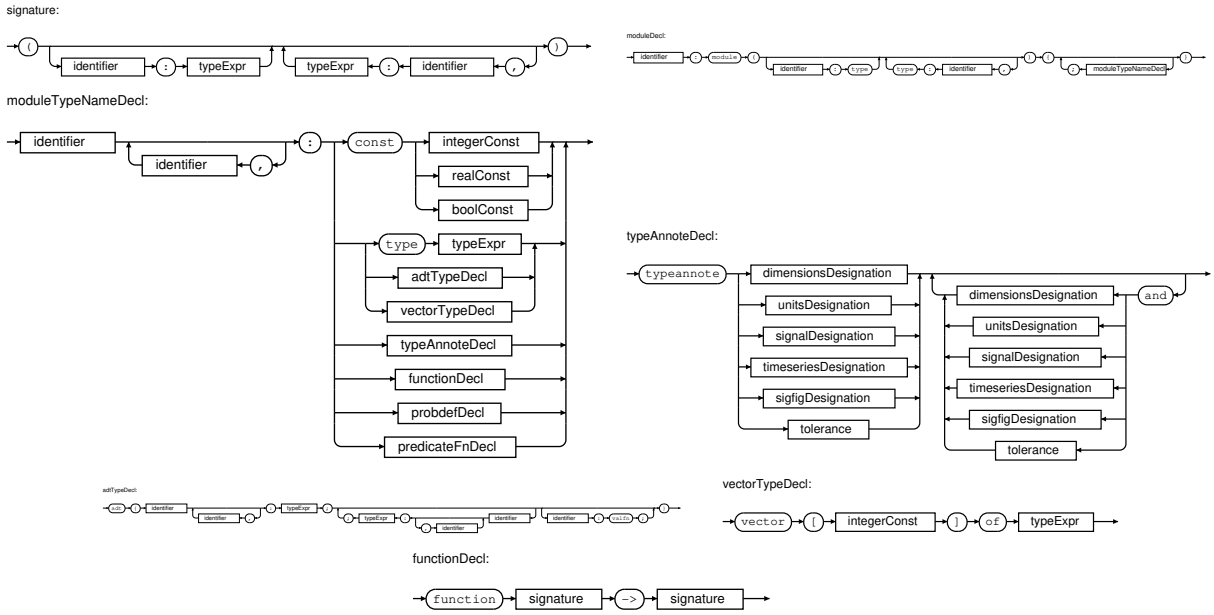


Fig. 9. Syntax diagrams for types, part 1.

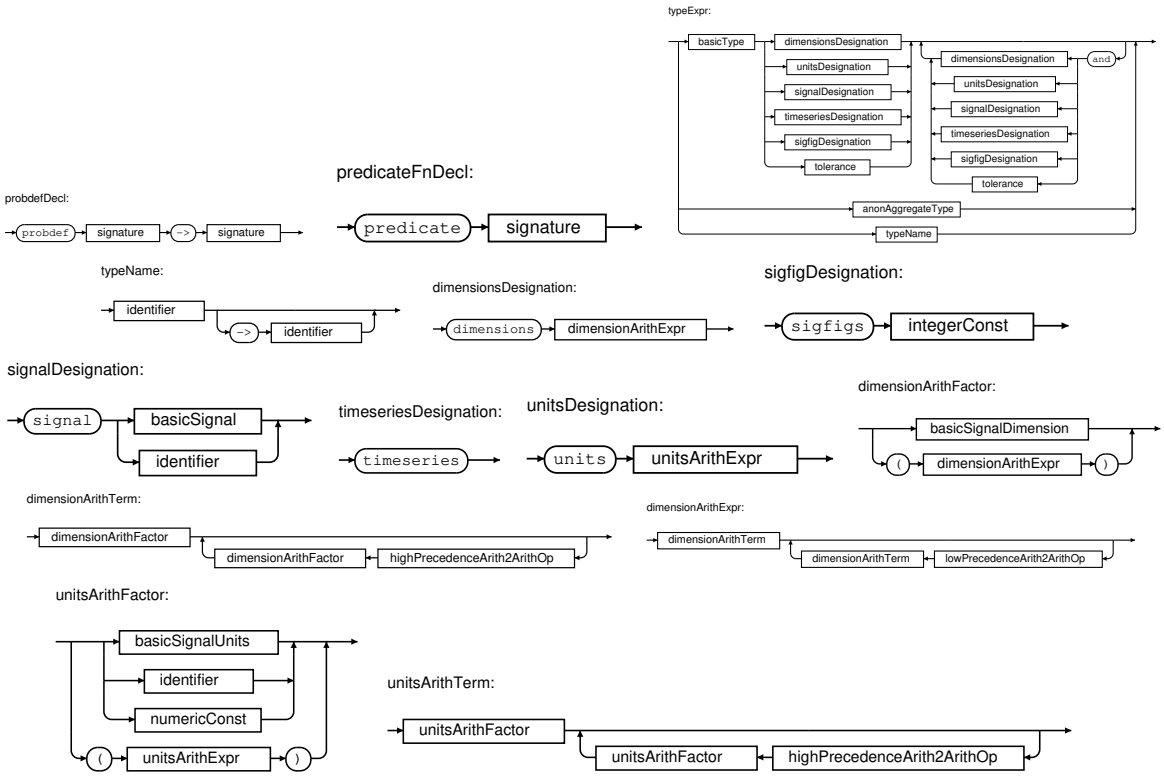


Fig. 10. Syntax diagrams for types, part 2.

DRAFT -- DRAFT -- DRAFT -- DRAFT -- DRAFT -

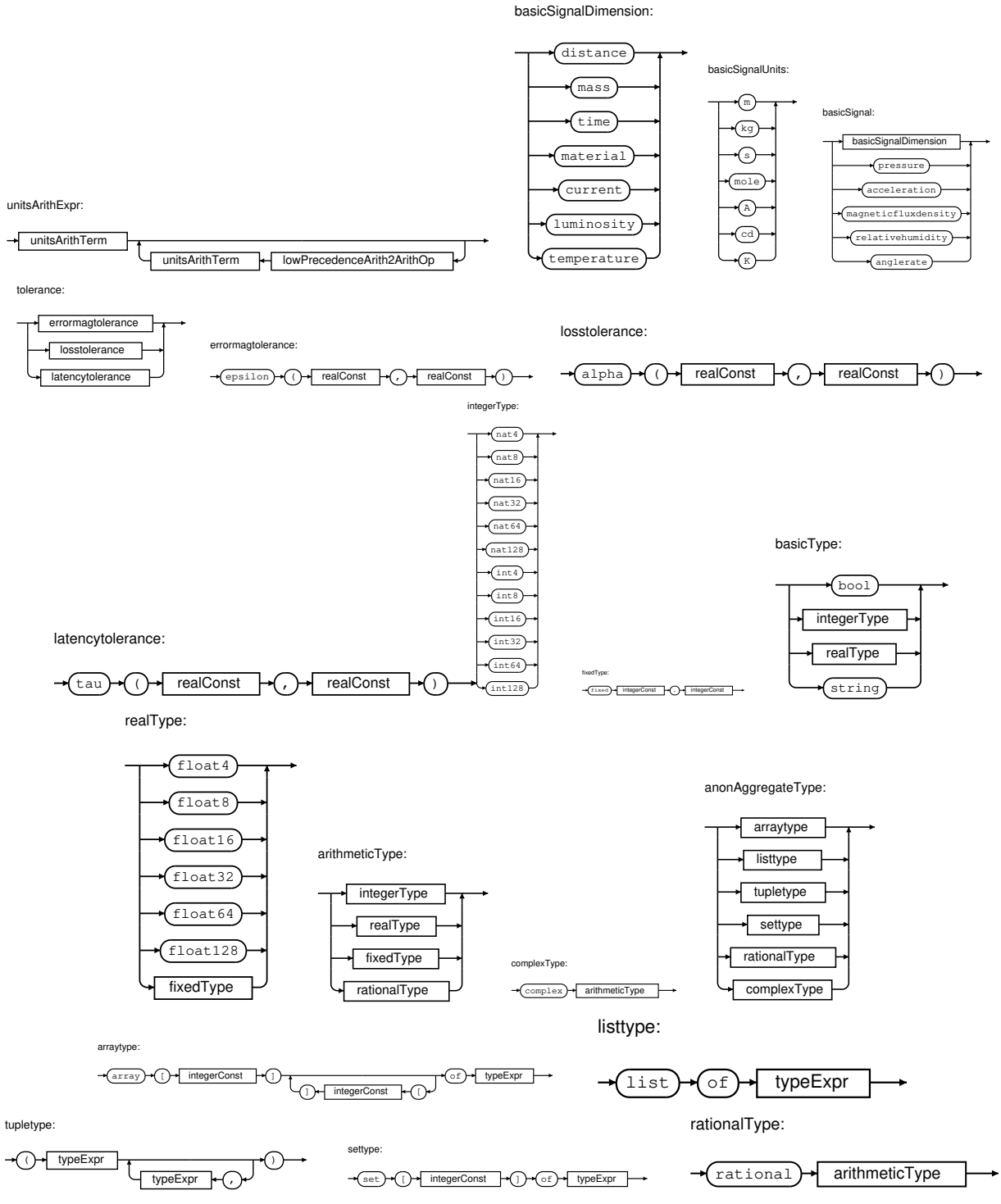


Fig. 11. Syntax diagrams for types, part 3.

DRAFT -- DRAFT -- DRAFT -- DRAFT -- DRAFT -

current, **luminosity**, **temperature**), one of five base signals (derived dimensions) (**pressure**, **acceleration**, **magneticflux**, **humidity**, **anglerate**), or one of the additional signals defined in a platform's Newton description.

The type collections are arrays, abstract data types (ADTs), lists, tuples and sets. Arrays are sequences of elements of a single type. ADTs and tuples are collections of elements of possibly different types; whereas an ADT collection has an associated *type name*, tuples are unnamed collections. Lists are collections of elements of a single type, with access to only the head of the list. Sets are unordered collections of elements, with primitive operations for union, intersection, relative complement and cardinality, with which idioms for other set operations (e.g., membership, subset) can be implemented[1]. The language types are discussed in more detail in Section 6, and a formal description of the type system is provided in Section B.

The sub-byte types (**bool**, **nat4**, **int4**, **float4**) are motivated by the fact that there are many classes of applications in which single bit values are semantically popular, e.g., for use as flags, as are variables taking on a small range of values [56]. In memory constrained devices, it makes sense to provide language constructs that support these idioms. Particularly for small cardinality, sets provide a means for memory and computationally efficient implementation of collections.

4.3 Variable and channel identifiers

There are two kinds of program-defined identifiers in Noisy: *variables* and *channels*. Variables are identifiers that are used to refer to possibly-structured data in memory. The simplest type of variable is a *pronumeral* that represents an item in memory with one of the basic arithmetic (numeric) types. Channels on the other hand are identifiers that programs use to refer to communication paths between functions. Channels as a programming language construct trace their roots to Hoare's *Communicating Sequential Processes (CSP)* [33]. Noisy channels are similar to channels in Alef [65], Limbo [50], Go [24], and to continuation variables in Cilk. The language-level communication operations are analogous to the **send_argument** operator for filling in values in a Cilk closure [12]. Noisy channels are tied to a *name* in the runtime name space.

While variables can be used in any expression (Section 4.8), channels can only be used in *send* and *receive* expressions. In a send expression, a program writes a value to a channel, while a program reads a value from a channel in a receive expression. The evaluation of a send expression does not complete until *another* function performs a receive operation on a channel that is associated with the same name in the runtime name space as the channel being written to. Likewise, evaluation of a receive expression will not complete until a send expression on a channel associated with the same name in the runtime name space is executed by another function.

Variables and channels must be defined before use, ascribing to the variable or channel a basic or collection type. Programs can also declare variables in conjunction with assignment, in which case it is ascribed the type of the value it is being set to. Example:

```
#       Variable 'sensor' is a channel of real-valued numbers,
#       with the constraint that the probability that the latency
#       on values on the channel being > 1 s is 0.1, and > 10 s is 0.0003

sensor : chan of int32 and tau(1, 0.1) and tau(10, 0.003);



#       Declare variable 'a' with type int
a       : int32;

#       Declare variable 'b' with tuple type (int, int)
b       : (int32, int32);

#       Define variable 'c' with type being the type of its assigned value (float32)
c       := 1.0;
```

4.4 Structuring programs

Programs are composed of *program types (modules)* and their implementations, a collection of *name generators (functions)*. A module is a unit of modularity that defines a set of types, constants, and name generators. The unit of compilation of programs

[1] Wirth [67] attributes the idea of sets as a language data type to Hoare, circa 1972.

DRAFT -- DRAFT -- DRAFT -- DRAFT -- DRAFT -

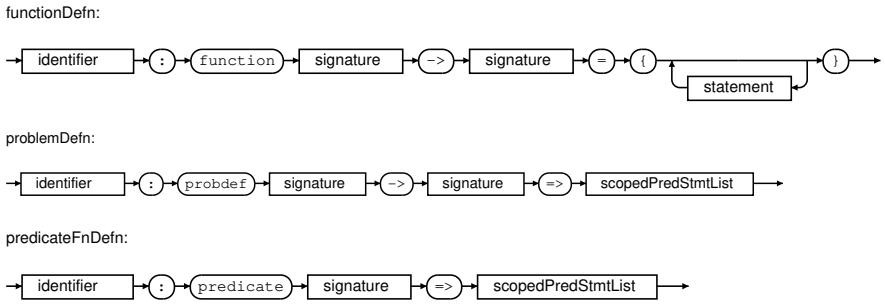


Fig. 12. Syntax diagram for function, problem definition, and predicate definitions.

is a single module and its implementation. This single complete program input to the compiler is used to generate one or more compiled outputs, corresponding to the pieces of the partitioned application. Partitioning occurs most easily at the level of individual functions. Due to the structure of the language and its runtime system, it is however possible to further partition a single function into smaller pieces.

A *name generator* or *function* is a collection of type declarations, variable definitions and statements. It is the unit at which applications get partitioned into executable units. There is no shared state between functions. The syntax diagrams for the grammar production for a valid function definition is shown in Figure 12.

All interaction between functions is explicitly through *names* in the runtime name space, via the binding of names to channels. A function definition includes an interface tuple type. This is the type structure of the name for write and read operations on the name. Example:

```
Math : module
{
        sqrt    : function (argument: float32) -> (result: float32);
        exp     : function (base: float32, exponent: float32) -> (result: float32);
}

#       The actual implementation of the Math module must have
#       definitions for the function types sqrt and exp:
sqrt : function (argument: float32) -> (result: float32) =
{
}

exp : function (base: float32, exponent: float32) -> (result: float32) =
{
}

#       A function that does not appear in the interface is declared
#       and implemented in one step here
someFunction : function (a: float32, b: float32) -> (result: float32) :=
{
        #
        #       This function uses ‘sqrt‘ and ‘exp‘
        #
        return (result: sqrt(argument: a) + exp(base: b, exponent: a));
}
```

```
#       Defines a function mul.

mul : function (multiplicand1: int16, multiplicand2: int16) -> (result: int16) =
{
}
```

DRAFT -- DRAFT -- DRAFT -- DRAFT -- DRAFT -

4.5 Scopes

The largest scope is the body of a function; there is no global scope. Within a function, a new scope is embodied by a collection of statements enclosed in braces (`{ ... }`). Variables defined within a scope have visibility only within the given scope. The following grammar productions introduce new scopes:

— **`modulebody`** production
— body of ADT type declaration
— **`scopedstmtlist`** production
— **`guardedscopelist`** production

The complete language grammar is provided in Appendix D.

4.6 Statements

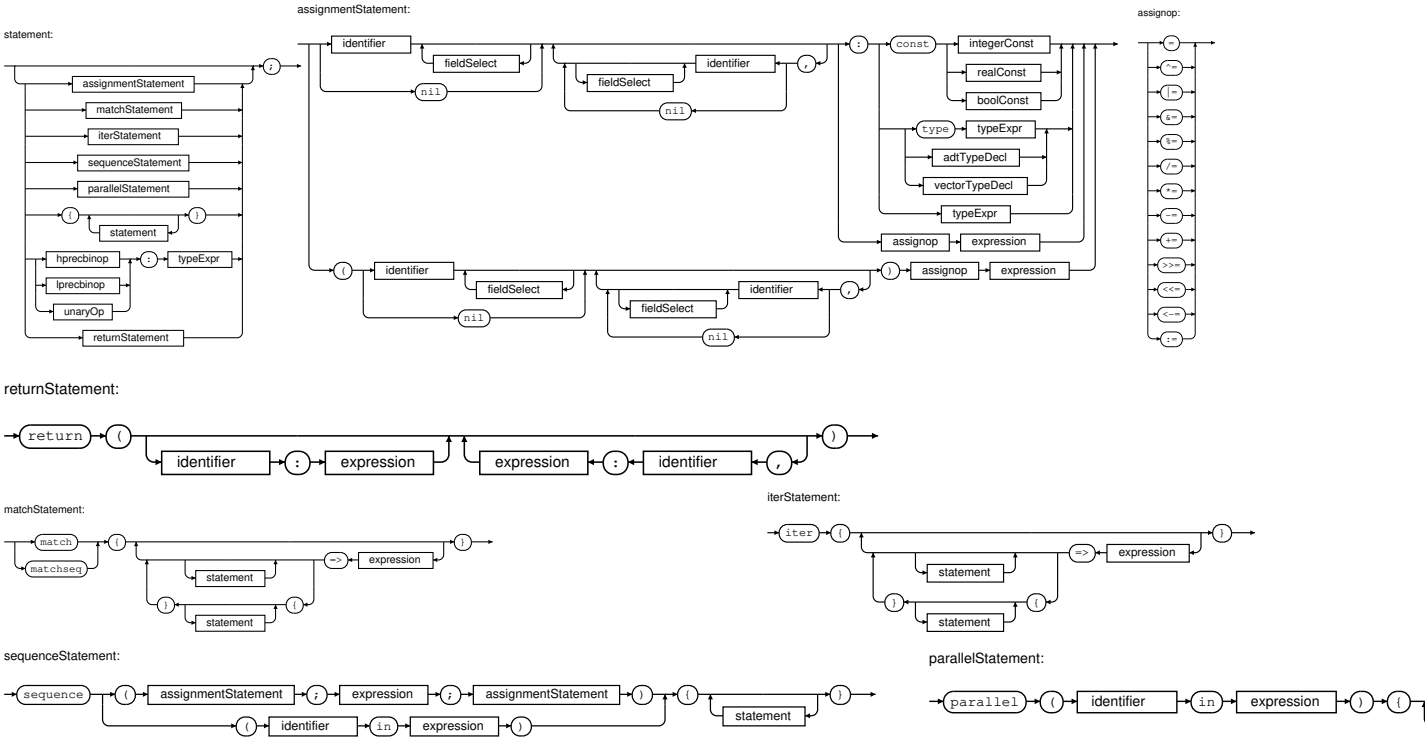


Fig. 13. Syntax diagrams for statements.

The statements which make up the body of a function define how it computes, creates names in the runtime name space, and communicates with other functions. Figure 13 shows the syntax diagrams for grammar productions corresponding to valid statements.

4.7 Assignment statements

The *r-value* in an assignment must be of the same type as the *l-value*, with the exception of an *l-value* of **`nil`**, which can be assigned an expression of any type; the *r-value* in such an assignment to **`nil`** is first evaluated, but the assignment operation does not yield any further action. The basic assignment operator is **`=`**. The additional assignment operators which have the form *binop***`=`** assign to the *l-value* the result of *l-value binop r-value*. Figure 13 illustrates the syntax diagrams for the associated grammar productions. Example:

DRAFT -- DRAFT -- DRAFT -- DRAFT -- DRAFT -

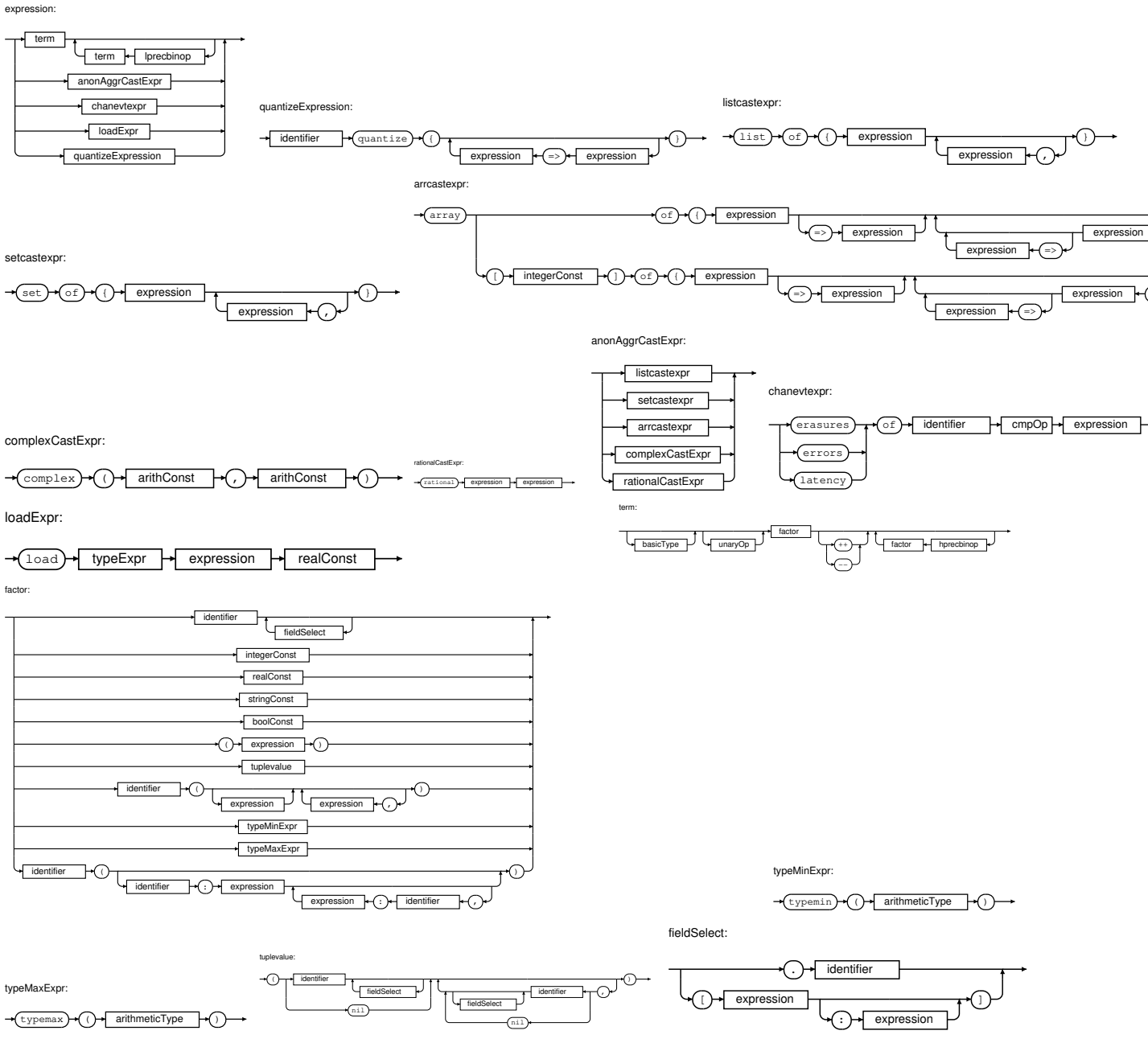


Fig. 14. Syntax diagrams for expressions.

```
#       Bit-wise negation of variable 'a'
a ^= 1;
```

4.8 Expressions

The associativity of operators is implicit in the definition of the grammar for expressions: *expressions* are made up of *terms* and the low precedence binary operators; terms are made up of *factors* and the high precedence binary operators; factors are

DRAFT -- DRAFT -- DRAFT -- DRAFT -- DRAFT -

l-values, constants, expressions in parenthesis or unary operators followed by a factor. The unary operators thus have the highest precedence, followed by high precedence binary operators and then low precedence binary operators. Figure 14 illustrates the grammar productions. Section 5 discusses operators in more detail.

4.9 The `match` and `matchseq` constructs

The **`match`** statement is a collection of guarded statement blocks. It executes *all* constituent statement blocks whose guards, which are Boolean expressions, evaluate to true. If multiple guards evaluate to true, the order in which the guarded statement blocks are evaluated is non-deterministic. The **`match`** statement is analogous to *guarded selection* in Dijkstra's guarded commands [22]. The **`matchseq`** statement on the other hand evaluates its guards sequentially, until a guard that evaluates to true. The guarded statements are then executed, and the **`matchseq`** statement completes. Figure 15 illustrates the syntax of **`match`** and **`matchseq`** statements with syntax diagrams.

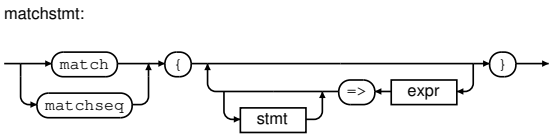


Fig. 15. Syntax diagrams for match statements

Programs can use the **`match`** statement to implement the equivalent of **`if`** statements (as in the Pascal and C family of languages), and multi-way selection statements such as Pascal **`case`** and C **`switch`** statements. Example:

```
#       If 'a' > 'b', 'max' = 'a',
matchseq
{
        a > b   =>      max = a;
        true    =>      max = b;
}
```

One possible implementation of a Fibonacci sequence generator function:

```
fibonacci : module
{
        fib : function (input: int16) -> (result: int16);
}

fib : function (input: int16) -> (result: int16) =
{
        #
        #       Reading the functionerator name yields the tuple of its read signature.
        #       Alternatively, accessing the names of the read signature variables is
        #       equivalent to triggering a read into variables with those names.
        #
        v := <-fib;

        matchseq
        {
                (v == 0) =>
                {
                        fib <-= 0;
                }

                (v == 1) =>
                {
                        fib <-= 1;
                }

```

DRAFT -- DRAFT -- DRAFT -- DRAFT -- DRAFT -

```
                true =>
                {
                        c1, c2 := name2chan int16 "fib";
                        c1 <-= (v - 1);
                        c2 <-= (v - 2);
                        r <-= <-c1 + <-c2;
                }
        };
}
```

Another implementation of a Fibonacci sequence generator function:

```
parfib : function (input: int16) -> (result: int16) =
{
        c1, c2 : int16;

        #
        #       Accessing the names of the read signature variables is
        #       equivalent to triggering a read into variables with those names.
        #
        matchseq
        {
                input == 0      => parfib <-= 0;
                input == 1      => parfib <-= 1;
                true    =>
                {
                        match
                        {
                        true    =>      c1 = name2chan int16 "parfib";
                                        c1 <-= (input - 1);

                        true    =>      c2 = name2chan int16 "parfib";
                                        c2 <-= (input - 2);
                        }

                        #
                        #       Accessing the names of the write signature variables is
                        #       equivalent to triggering a write into variables with those names.
                        #
                        result = <-c1 + <-c2;
                }
        }
}
```

In the above example, the inner **`match`** statement is used to initiate two Fibonacci number computations without restriction on the ordering (i.e., they could potentially execute in parallel).

4.10 The `if else` construct

The **`if else`** statement is a C-style conditional.

4.11 The `iter` construct

The **`iter`** statement is a repetitive collection of guarded statement blocks. It executes repeatedly while any of its guards, which are Boolean expressions, evaluate to true. The **`iter`** statement is analogous to *guarded iteration* in Dijkstra's guarded commands [22]. All statements whose guards evaluate to true execute. The syntax of **`iter`** statements is illustrated by the syntax diagrams in Figure 16.

4.12 The `sequence` and `parallel` construct

The **`sequence`** statement C-style looping construct (like **`for`** in C). The **`parallel`** is a concurrent iteration construct.

DRAFT -- DRAFT -- DRAFT -- DRAFT -- DRAFT -

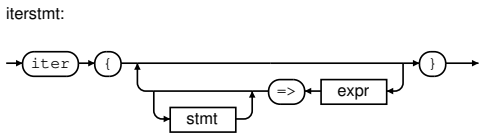


Fig. 16. Syntax diagrams for **`iter`** statements

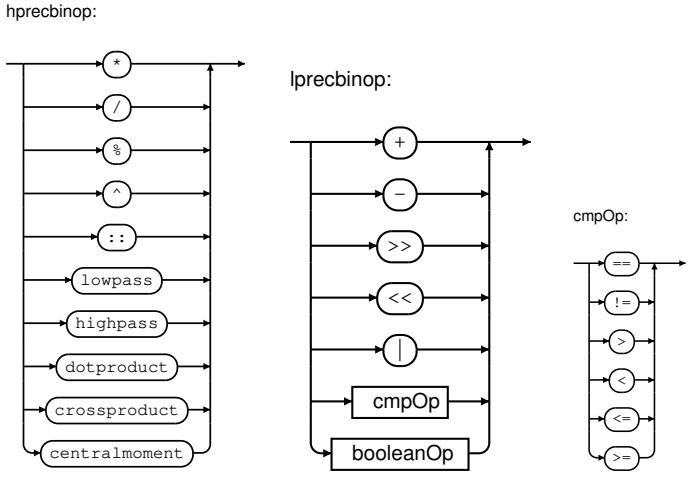


Fig. 17. Syntax diagrams for operators and their classifications.

5. OPERATOR DESCRIPTIONS

The semantics of the language-level operators are presented in the following sections. The language includes operators for operation on *values*, operators on *names* and operators on *channels*. The language-level operators and their semantics are listed in Table 1 and Figure 17.

The `][` operator, when applied to an expression, yields the dimensions of the expression. The `}{` operator applied to an expression yields the units of the expression. The `><` operator applied to an expression yields the relative uncertainty of the expression, a real number between 0 and 1 denoting the relative uncertainty of the expression[2].

5.1 Operators on channels

There are two operators on channels, a channel send (*channel* `<-=` *expr*) and a channel receive (*variable* or **`nil`** `<-` *channel*). Channel communication is unbuffered, rendezvous: a send (receive) completes when a matching receive (send) is performed at the other end of the channel.

All interaction between functions is over a channel. Since functions might be executing locally or remotely, the passage of references down a channel is not permitted. E.g., a channel cannot be passed down a channel.

6. TYPES

The syntax of type declarations and definitions were previously provided in Section 4. This section provides further detail on the language base types, as well as the construction of collection types.

The language includes a small set of basic types—**`bool`** (Booleans), **`nat4`**, **`nat8`**, **`nat16`**, **`nat32`**, **`nat64`**, **`nat128`**, (natural numbers) **`int4`**, **`int8`**, **`int16`**, **`int32`**, **`int64`**, **`int128`**, (integers) **`float4`**, **`float8`**, **`float16`**, **`float32`**, **`float64`**, **`float128`**, (floating-point approximate real numbers) **`fixed`** (fixed-point approximate real numbers), **`rat`** (rational numbers), and **`string`**. The arithmetic types are the Booleans, natural numbers, integers, floating-point, fixed point, and rational numbers. The basic language data types may be employed in

[2]We could make this statically checkable by defining the semantics as the worst-case uncertainty, but that would make it fairly useless as the worst-case might often simply be 1.0.

DRAFT -- DRAFT -- DRAFT -- DRAFT -- DRAFT -

Table 1. Noisy language operators.

Operator	Description
`.`	ADT member access
`[]`	Array or character string subscript
`]`*arg*`[`	Obtain dimensions of *arg*
`}`*arg*`{`	obtain units of *arg*
`>`*arg*`<`	obtain relative uncertainty of *arg*
`!`	Logical not
`~`	Bitwise not
`++`	Increment
`--`	Decrement
`load`	Load a module
type	Type cast
`*`, `/`, `%`	Multiplication, division, modulo
`+`	Unary plus, addition, set union, string concatenation
`-`	Unary minus, subtraction, set difference
`«`	Logical left shift
`»`	Logical right shift
`**`	Exponentiation
`<`	Less than
`>`	Greater than
`<=`	Less than or equal to
`>=`	Greater than or equal to
`==`	Equals
`!=`	Not equals
`>=<`	Is permutation of
`&`	Bitwise AND, set intersection
`^`	Bitwise XOR
`|`	Bitwise OR
`::`	List append
`&&`	Logical AND
`||`	Logical OR

Operator	Description
`=`	Assignment
`:=`	Declaration and assignment
`+=`	Addition/concatenation/union assignment
`-=`	Subtraction/difference and assignment
`*=`	Multiplication and assignment
`/=`	Division and assignment
`%=`	Modulo and assignment
`&=`	Bitwise AND and assignment
`|=`	Bitwise OR and assignment
`^=`	Bitwise XOR and assignment
`«=`	Logical left shift and assignment
`»=`	Logical right shift and assignment
`<-`	Assignment to/from channel
`head`	List head value
`tail`	List tail value
`length`	List, array, or string length; set size
`sort`	List, array, or string length; sort by `valfn`
`reverse`	List, array, or string length; reverse by `valfn`
`tintegral`	Integral over time of a `timeseries` variable
`tderivative`	Derivative with respect to time of a `timeseries`
`fourier`	Compute the discrete Fourier transform of a `timeseries`
`timebase`	Obtain sampling time indices of a `timeseries`
`samples`	Obtain sample data from a `timeseries`
`uncertainty`	Obtain posterior distribution of uncertainty for a `signal`
`centralmoment`	Compute the nth central moment of a distribution
`lowpass`	Low-pass filter a `timeseries`
`highpass`	High-pass filter a `timeseries`
`sigfigs`	Obtain number of significant figures of a `signal`
`dotproduct`	Compute the inner product of two `vector` variables
`crossproduct`	Compute the vector product of two `vector` variables
`typemin`	Give the maximum value that an arithmetic type can take
`typemax`	Give the minimum value that an arithmetic type can take
`=>`	Implication (a binary infix operator)

aggregate collections. The collection data types are arrays, tuples, ADTs (aggregate data types), lists and sets. Channels may be defined to carry any of the basic or aggregate data types, but these cannot include channels. Type definitions for the language base types may have an optional *error tolerance constraint*.

In addition to the basic types that can be used in type expressions, an identifier can also be of types `module`, `function` or act as an alias for a type expression. In the cases of modules and functions, the type signatures are functions of the body of the module definition, and that of the function channel interface, respectively. ADTs and type aliases introduce new *type names*.

6.1 Reference versus value types, channels and `nil`

All the primitive and aggregate types of variables are value types. Channels are reference types (they have *implicit state*), and may not be passed down channels. A primitive or aggregate variable cannot be transmitted down a channel if it contains a channel within it. Since the equivalent of function calls are communications on channels, and as previously stated, these communications can only carry values, it could be said that the semantics for interaction between program components are *call-by-value*. Treating all types as value types should not be thought of as an inefficiency burden as an implementation can use a copy-on-write strategy to make computation within a function efficient.

6.2 Specifying tolerance constraints

For some variables in programs, it might be known that a certain degree of deviation from their correct values is acceptable. In the case of channels, a certain degree of erasures might be tolerable. Tolerance constraints on variables and channels, is key to being able to use the mathematical analysis of error magnitudes in programs [56] to implement forward error correction on the

DRAFT -- DRAFT -- DRAFT -- DRAFT -- DRAFT -

values exchanged between functions. Conversely, it enables deliberate changes in functionality that improve performance but might induce errors.

For example, values to be transmitted on a communication channel might be occasionally purposefully dropped to reduce power consumption or improve *overall* network performance, while staying within prescribed constraints. As another example, in an application partitioned over devices that communicate over a wireless medium, the transmit power consumption might be purposefully reduced at the cost of a higher (tolerable) bit error rate. The low-level communication encodings are thus tuned to *application error tolerance properties*. We could think of the error tolerance constraints exposing semantic information that enables application-specific source and/or channel coding.

The most flexible form in which constraints specifying *tolerable error* could be provided, would be as a *tail distribution* on error magnitude. For example, it might be desirable that the probability that the magnitude of error in a variable is greater than x should vary with x as $\frac{1}{x}$. The notational complexity of representing such error tolerance constraints would be significant: since it is logical for the error tolerance constraint to be placed in the type annotation, the type would then need to contain an expression in a variable (x in the above example). This approach is therefore avoided. Experience with the language and error tolerance constructs may necessitate revisiting this restriction.

Instead of such general error tolerance constraints, the language design includes a restricted form of the above in which x is constant. An error tolerance constraint is thus defined in terms of two variables, m and A, specifying that the probability the magnitude of error in a variable is greater than m, should be less than A, i.e., $\Pr\{M > m\} \leq A$. A type expression involving the basic types can be qualified with one or more error, erasure or latency tolerance constraints. For example, the following declares a variable **`pixel`**, of type **`(nat8, nat8, nat8, nat8)`**, with the error constraint that the probability that the magnitude of error (due to erasures or errors) in a member of the 4-tuple exceeds 4 should be 0.01:

```

t       : type int32 epsilon(4, 0.01);
pixel   : (t, t, t, t);
```

Latency tolerances are inherently at odds with error and erasure tolerances. With errors and erasures, one can introduce redundancy in the form of encoding to mitigate the effects of the undesirable phenomena. In the case of latency tolerances on the other hand, one must reduce redundancy to improve (decrease) latency (transmission time). On the other hand, the violation of latency tolerances can be easily checked in an implementation (e.g., via timers), whilst the violation of error magnitude tolerances is more involved: violation of the tolerance inherently means the decoding process wrongly decoded an erroneous codeword because it had more errors than that which could be corrected based on the minimum Hamming distance in the chosen code[3].

The goal of error and erasure tolerances in the current implementation is to address the problem of errors and erasures in the communication links between a partitioned application (between its constituent functions). Tolerance constraints specified for channels apply to the values communicated on the channel. Tolerance constraints specified for variables are not used to encode the variables, but rather propagated upward through the dataflow graph to channels, reads from which reach the variables with tolerance constraints. Although a bit more difficult to reason about, the encodings also benefit values in programs, not only values communicated over a network (over channels): all variables can be thought of as channels to memory. This semantically exposes the fact that a read or a write from a "variable" might either mean reading from a local on-chip memory, or from a memory across the network, and the error tolerance associated with that "variable" might therefore either be used for bus encoding for error detection or forward error correction to a local memory, or for encoding a communication that happens over the network. A future implementation of the compiler could use the tolerance information on variables to encode the variables themselves, in order to mitigate the effect of soft-errors in memories, in an application-specific manner.

6.3 Types **`bool`**, **`nat4`**, **`nat8`**, **`nat16`**, **`nat32`**, **`nat64`**, **`nat128`**, **`int4`**, **`int8`**, **`int16`**, **`int32`**, **`int64`**, **`int128`**, **`float4`**, **`float8`**, **`float16`**, **`float32`**, **`float64`**, **`float128`**, **`fixed`**, and **`rat`**

The primitive types **`bool`**, **`nat4`** are unsigned quantities with sizes 1 and 4 bits respectively; the remaining natural number types follow similarly. The type **`int4`** is a signed 4-bit value in two's complement format; the remaining integer types follow similarly. The fixed point approximate real numbers, **`fixed m.n`**, are signed $m + n + 1$-bit binary fixed point values in which m bits are used to represent the whole component, n bits are used to represent the fractional component, and one bit is used to represent

[3] The minimum distance of a code, $d(C) \geq \delta \iff C$ is $\delta - 1$ error correcting. $d(C) \geq 2\epsilon + 1 \iff C$ is ϵ error correcting [10].

DRAFT -- DRAFT -- DRAFT -- DRAFT -- DRAFT -

the sign. The floating point approximate real numbers, e.g., **float32** are in 32-bit IEEE-754 double precision floating point format, with the **float8** and **float4** types being quarter- and eighth-precision floating point in the style of IEEE 754.

6.4 Type **string**

Strings are sequences of Unicode characters. An element in a string (a character), obtained using the notation *string_identifier[index]* is a 16-bit value. Strings can be concatenated using the **+** operator. The **length** operator, applied to a string yields the number of characters in the string. A substring or *slice* of a string is obtained using the notation:

string_identifier[start index (optional) ':' end index (optional)]

and yields a string. When the start (end) index is absent, it is implicitly the first (last) element of the string. The empty string "" is represented by the value **nil**. Examples:

```
#       Define a new string 'name'
phrase  := "Mountains made of steam";

#       The variable c has type 'int', and holds the character 'M'
c       := phrase[0];

#       This sets the variable 'q' to "made of steam"
q       := phrase[length "Mountains ": ];
```

6.5 The **array** collection type

Arrays hold sequences of items of a single type. Multi-dimensional arrays are stored in memory in row-major order. The storage for arrays is conceptually allocated at the point of definition, thus there is no distinction between array declaration and array definition as there does in some languages. An element in an array is obtained using the notation *array_identifier[index]*. The **length** operator applied to an array yields the length of the array. A *slice* of an array is obtained using the notation:

array_identifier[start index (optional) ':' end index (optional)]

and yields an array of the same type. The type of an array includes its length, and thus all declarations of arrays include a specification of their length. However in an array definition from initializers, the dimensions may be omitted as they are implicit in the initializer. Example:

```
#       Declare 1-dimensional array 'a' of nat4s with 32 elements
a               : array [32] of nat4;

#       Declare a 3-dimensional array 'volume' of bits, and set one point
volume          : array [128][128][128] of bool;
volume[0][0][1] = 1;

#       Define a 3-dimensional array 'volume' of bits
volume2         := array [128] of {* => array [128] of {* => array [128] of bool}};

#       Definition of an array, type implicit from initializers,
firstArray      := array of {"oil", "and", "water", "don't", "mix"};

#       Definition of an array, type implicit from initializers, with size 32
secondArray     := array of {"oil", "and", "water", "don't", "mix", 31 => "."};

#       Definition of an array, type implicit from initializers, size 32;
#       the last 27 entries contain "."
thirdArray      := array [32] of {"oil", "and", "water", "don't", "mix", * => "."};
```

6.6 Tuple collection type

A tuple is an unnamed collection of items of possibly different type. A tuple type might be considered as a cartesian product of type expresisons. The elements in a tuple cannot be accessed individually; assignment to a tuple must be from a tuple expression,

DRAFT -- DRAFT -- DRAFT -- DRAFT -- DRAFT -

and assignment from a tuple type must be into a tuple of variables. Thus any assignment to a tuple, sets all fields. Example:

```

#       Declare color to be a tuple type
color   : (nat8, nat8, nat8, nat8);

color = (0, 6, 32, 8rFF);
```

6.7 Aggregate Data Type (ADT) collection type

ADTs are similar to tuples, with the only difference being that the members of an ADT may be named. An ADT declaration introduces a new type name, and subsequently, variables may be declared with that type name. Assignments from tuples with the same order and type of variables are permitted to ADT instance variables. Example:

```

#       Define an ADT type Color
Color : adt
{
        r : nat8;
        g : nat8;
        b : nat8;
        a : nat8;
};

#       Declare a variable with type Color
c : Color;

#       Assign a tuple to the ADT instance
c = (0, 6, 32, 8rFF);
```

6.8 The `set` collection type

The **`set`** collection data type is used to represent unordered collections of data items. A set can be cast to a list of the same type, yielding a non-deterministic ordered list. A list can likewise be cast as a set. The operations defined on set variables are *set union* ($A \bigcup B$ is denoted by `A + B`), *set intersection* ($A \bigcap B$ is denoted by `A & B`), *set difference or relative complement* ($A \bigcap \overline{B}$ is denoted by **`A - B`**) and *set cardinality* ($|S|$ is denoted by **`length S`**). The type of a set includes its cardinality, and thus all declarations of sets include a specification of their cardinality. However in a set definition from initializers, the cardinality may be omitted as it is implicit in the initializer. Multiplicity of elements is ignored (i.e., **`set`**s are not *multisets*). An empty set has the value **`nil`**. Examples:

```

#       Declare 's' as a set with cardinality 32, of integers
s       : set [32] of int32;

#       Add a few elements to the set
s       += set of {2, 3, 5, 7, 11, 13, 17, 19, 23, 29, 31, 37, 41};

#       Check for set membership
u7p     := s   &   set of {7};
```

6.9 Noisy `probdefs`

Noisy allows programmers to specify the computation problem that a given function solves, using **`probdef`** definitions. Noisy **`probdef`** definitions use logic to specify relationships (predicates) that must hold between the functions read type and its write type.

6.9.1 *Why Noisy* `probdefs`.

Stored-program computers and their realizations in the form of microprocessors, mechanize the solution of *algorithms*, by implementing a computation model analogous to an efficient Turing machine. The primary reason for

DRAFT -- DRAFT -- DRAFT -- DRAFT -- DRAFT -

the pervasiveness of computers in modern society is their ability, through this mechanization of algorithm execution, to be used in the solution of *computational problems* of various kinds.

The computational problems of interest in computing applications can however often be described independent of specific algorithms for their solution [40]. This facilitates the harnessing of the potential for multiple algorithm choices, or implementations thereof, to achieve improved performance transparent to end users of computing systems—in much the same way that clock frequency gains, in the past decade, led to improvements in third party applications through simple processor upgrades.

Analogous to the description of specific algorithms with imperative instruction sequences, computational problems can be described with declarative statements which are independent of the algorithms that might be used for their solution. Results from the domain of descriptive complexity theory [37] show that problems whose solution can be proven to be within the polynomial time hierarchy (PH), including the subclass of problems whose solution can be checked in polynomial-time (NP), and those that can be solved in polynomial time (P), can be described in second-order logic (SOL).

The correspondence between computational problems and the worst-case computational complexity of algorithms for their solution, is the subject of investigations in the area of descriptive complexity [36; 37]. For example, results from this area indicate that any problem that can be expressed in first-order logic with the addition of a least-fixed-point operator (FOL(LFP)) can be solved in worst-case time polynomial in the size of their inputs (i.e., computational class P).

A description of a problem may be utilized in a variety of ways. Historically, partial descriptions of problem properties, capturing critical invariants that are a precondition (but not necessarily sufficient) for correct execution, have been captured in programs as *assertions*. Assertions have found uses ranging from proactively catching bugs in programs, to the facilitation of construction of proofs about program correctness. Programming languages such as Prolog [21] have also been built on first-order logic (FOL, a subset of SOL), and have achieved the ability to express general computational problems beyond the restriction of FOL. Prolog programs consist of a collection of Horn clauses. Horn clauses are disjunctions with at most one true term, i.e.,

$$\neg T_1 \vee \neg T_2 \vee \ldots \neg T_n \vee P \tag{1}$$

and can thus also be seen as implications

$$\neg T_1 \vee \neg T_2 \vee \ldots \neg T_n \vee P \equiv (T_1 \wedge T_2 \wedge \ldots T_n) \Rightarrow P. \tag{2}$$

The term P to the right of the implication can be interpreted in Prolog to be a procedure name (the term on the left of the implication is considered to be a "goal" query). Recursion can be defined in this manner by having terms that appear on both sides of an implication (and thus procedures defined in terms of themselves).

Logic programming languages such a Prolog are typically also classified as being declarative. While the core of Prolog is first-order and propositional Horn clauses, real uses of Prolog for even the most basic algorithms utilize non-first-order constructs, recursion, and statements with side effects. Propositional and first-order Horn clauses are a subset of first-order logic, and are argued to be, in the context of their use in languages such as Prolog, Turing complete. First-order logic is however not sufficient to describe problems in complexity classes above AC^0; the argued Turing-completeness thus seems to be achieved through recursion, via the particular means by which Prolog programs are evaluated (SLD resolution).

6.9.2 *Background: Propositional logic, first and second order logic, and assertions for representing programs.* The language of propositional calculus (propositional logic) permits the definition of formulae comprising variables and constants joined together by conjunctions and disjunctions. First-order logic, (predicate logic, predicate calculus) extends propositional logic with the addition of quantifiers ($\forall$, $\exists$) over atomic values.

Concrete sets are collections of (multi-dimensional tuples of) items drawn from some (multi-dimensional) domain or universe of elements. Abstract sets describe, not sets of concrete elements, but collections with prescribed properties. The properties may be in terms of propositional, first-order, or higher-order logic predicates; in the case of the latter, the predicates may have quantifiers over sets, as opposed to quantifiers over atomic values in first-order logic.

The description of the properties (expressed in the language of mathematical logic) satisfied by the output results of a program, as a set of propositions (or axioms), was proposed by Hoare [30; 32]. Given a set of properties, and the axioms defining the behavior of a particular language (governing constructs such as assignment, implication, composition or iteration), it is possible to prove properties about the execution of a given program and input.

In practical use, the properties satisfied by end results or intermediate values of programs may be thought of as (and, indeed, are often annotated as) assertions. These assertions may serve as documentation of the intended results of a program (for an end-user, or for a programmer extending the program), or may be used to proactively find bugs, or may serve in the proof of

DRAFT -- DRAFT -- DRAFT -- DRAFT -- DRAFT -

properties of the program. Such proofs will take as input assertions about the behavior of the program, and axioms about the behavior of the machine on which they execute [32; 34]. In typical use, assertions cover a subset of the properties or behavior of a program. A program may however also be represented by the the strongest predicate which holds for every possible behavior [26; 27; 31].

6.9.3 *Noisy* **probdef***s versus declarative programming.* Declarative languages, when compared to imperative ones, are often described informally as "specifying what to do, not how to do it." This informal definition is misleading, since most declarative languages enable the specification of algorithms—particular methods for structuring the computation of solutions to problems. In practice, languages that are referred to as declarative do however minimize or completely eliminate the specification of explicit control flow via iteration, and instead achieve control flow through recursion (typically, functional languages [8]), run-time iteration over statements until a fixed-point is reached [16; 17], or synthesis of the control-flow surrounding the basic scaffolding of an algorithm, at compile time [55]. Broy [14] provides a more precise definition of declarative programs and specifications. In contrast to declarative *programming*, problem definition languages such as Sal **??** do not even specify *what* to do—they only specify what the state of a system will be once the solution of a problem is complete; while such problem definitions might implicitly include some requirements on eventual sequencing of operations, the only such implicit ordering is that due to true (read-after-write) dependences. Most importantly, problem definition languages are *non-procedural* [44; 64], providing no specification of how computation should proceed, whether through explicit iteration or implicit sequencing through recursion.

6.9.4 *From declarative specifications to imperative programs.* Given a declarative specification, a number of techniques can be used to elaborate the specification to achieve its solution. If the specification corresponds to variables ranging over finite universes, they may be solved with constraint programming solvers or satisfiability modulo theories (SMT) solvers [1; 2]. A number of other techniques have been investigated for *automatic programming*—synthesis of programs from declarative (or other forms of partial) program specifications.

Imperative programs without explicit control flow ordering written in Chandy and Misra's UNITY language may be compiled to imperative C programs with explicit flow control [49]. Expressions in L_1 [15], a subset of SETL [52] with constructs such as imperative **for** have been shown to be synthesizable to imperative programs guaranteed to be computable in worst-case linear time and space. In a similar vein, Itzhaky et al. [38] synthesize second-order logic formulae to application-specific logics that are known to be translatable to linear-time imperative specifications, while Clark and Darlington [19] have studied synthesizing recursive sorting algorithms from first-order predicate logic specifications.

Sketches (the Sketch language) and combinatorial synthesis [54] enable a programmer to provide an incomplete imperative program containing *holes*, which may be, among other things, missing constants, variable initializers, polynomial expressions, and so on. A code synthesizer is used to fill these holes such that the resulting program meets a previously provided specification, to arrive at the sketch's *completion*. The specifications against which sketches are checked are complete imperative programs that are typically implemented using a simple, easy-to-understand algorithm solving the problem of interest. Like Sketches, Srivastava et al. [55] present techniques for program synthesis for *specific algorithms* (e.g., for Strassen's algorithm for matrix multiplication), from a higher-level specification, including the loop nests (and is thus not algorithm-independent). Requiring even less detail in the specification from a programmer's part, Harris and Gulwani [25] present methods to synthesize programs directly from examples of input-output pairs.

6.10 Problem definitions for functions

```
#
#       For kMathPi, cos, and sin (we need both the function prototype as well as the probdef prototype)
#
include "math.nd"

#
#       The module definition gives its signature for other
#       modules (e.g., the runtime system) that want to execute
#       it.
#
#       The module definition need not export the function init
#       if it is not intended to by loaded by the "conventional loader"
#       (e.g., the OS shell).
```

DRAFT -- DRAFT -- DRAFT -- DRAFT -- DRAFT -

```
#
Dft : module (sampleType: type, indexType: type)
{
        dft     : function (N: indexType, x: array [N] of complex sampleType) -> (X: array [N] of complex sampleType);
        dft     : probdef (N: indexType, x: array [N] of complex sampleType) -> (X: array [N] of complex sampleType);
}


#
#       The probdef is transliterated from dft.cpd
#
#       See R. Jongerius and P. Stanley-Marbell
#       "Language Definition for a Notation of Computational Problems",
#       IBM Research Report rz 3828, IBM Research, 2012.
#
#       DFT
#
dft     : probdef (N: indexType, x: array [N] of complex sampleType) -> (X: array [N] of complex sampleType) =>
{
        #
        #       The outer 'given (X...)' is not needed since N, x, and X are already
        #       bound to the read / write types of the function
        #
        given (X in array [N] of complex sampleTyp)
        (
                exists (expRes in array [N][N] of complex sampleType)
                (
                        forall (k, n in indexType)
                        (
                                (
                                        k >= 0                                                          &&
                                        k < N - 1                                                       &&
                                        n >= 0                                                          &&
                                        n < N - 1                                                       &&
                                        (real expRes[k][n]) == cos(-2 * kMathPi * n * k / N)            &&
                                        (imaginary expRes[k][n]) == sin(-2 * kMathPi * n * k / N)
                                ) =>
                                (real X[k]) == sum n in indexType from 0 to N - 1 of (real              x[n]*expRes[k][n]))     &&
                                (imaginary X[k]) == sum n in indexType from 0 to N - 1 of (imaginary     x[n]*expRes[k][n]))
                        )
                )
        )
}
```

6.11 Predicate functions

```
#
#       The module definition gives its signature for other
#       modules (e.g., the runtime system) that want to execute
#       it.
#
#       The module definition need not export the function init
#       if it is not intended to by loaded by the "conventional loader"
#       (e.g., the OS shell).
#
#
#       This formulation is similar in style to the SlowConvexHull algorithm
#       given on page 3 of de Berg, van Kreveld, Overmars & Schwartzkopf.
#
#       The sign of the determinant
#
```

DRAFT -- DRAFT -- DRAFT -- DRAFT -- DRAFT -

```
#                       | 1 px py |
#               D =     | 1 qx qy |  = (qx*ry - qy*rx) - px(ry - qy) + py(rx-qx),
#                       | 1 rx ry |
#
#       denotes whether r is on left or right of line pq.
#
#       The module type parameter 'coordType' is the type used for sub-coordinate values.
#
ConvexHull : module (coordType: type)
{
        convexHull              : function (inputPoints: list of (coordType, coordType)) -> (convexHull: list of (coordType, coordType));
        convexHull              : probdef (inputPoints: list of (coordType, coordType)) -> (convexHull: list of (coordType, coordType));

        pqDiffer                : predicate (qx:coordType, qy:coordType, px:coordType, py:coordType);

        nonNegativeDeterminant  : predicate (qx:coordType, qy:coordType, rx:coordType, ry:coordType, px:coordType, py:coordType);
        qOnUpperRight           : predicate (qx:coordType, qy:coordType, rx:coordType, ry:coordType, px:coordType, py:coordType);
        qOnUpperLeft            : predicate (qx:coordType, qy:coordType, rx:coordType, ry:coordType, px:coordType, py:coordType);
        qOnLowerLeft            : predicate (qx:coordType, qy:coordType, rx:coordType, ry:coordType, px:coordType, py:coordType);
        qOnLowerRight           : predicate (qx:coordType, qy:coordType, rx:coordType, ry:coordType, px:coordType, py:coordType);
        qOnRight                : predicate (qx:coordType, qy:coordType, rx:coordType, ry:coordType, px:coordType, py:coordType);
        qAbove                  : predicate (qx:coordType, qy:coordType, rx:coordType, ry:coordType, px:coordType, py:coordType);
        qOnLeft                 : predicate (qx:coordType, qy:coordType, rx:coordType, ry:coordType, px:coordType, py:coordType);
        qBelow                  : predicate (qx:coordType, qy:coordType, rx:coordType, ry:coordType, px:coordType, py:coordType);
}

#
#       Several predicate functions for the eventual problem definition
#
pqDiffer : predicate (qx:coordType, qy:coordType, px:coordType, py:coordType) =
{
        !((qy == py) & (qx == px))
}

nonNegativeDeterminant : predicate (qx:coordType, qy:coordType, rx:coordType, ry:coordType, px:coordType, py:coordType) =>
{
        ((qx*ry - qy*rx) - px*(ry - qy) + py*(rx - qx)) >= 0
}

qOnUpperRight : predicate (qx:coordType, qy:coordType, rx:coordType, ry:coordType, px:coordType, py:coordType) =>
{
        ((qy > py) & (qx < px) & nonNegativeDeterminant(qx, qy, rx, ry)@(px, py))
}

qOnUpperLeft : predicate (qx:coordType, qy:coordType, rx:coordType, ry:coordType, px:coordType, py:coordType) =>
{
        ((qy > py) & (qx > px) & nonNegativeDeterminant(qx, qy, rx, ry)@(px, py))
}

qOnLowerLeft : predicate (qx:coordType, qy:coordType, rx:coordType, ry:coordType, px:coordType, py:coordType) =>
{
        ((qy < py) & (qx < px) & nonNegativeDeterminant(qx, qy, rx, ry)@(px, py))
}

qOnLowerRight : predicate (qx:coordType, qy:coordType, rx:coordType, ry:coordType, px:coordType, py:coordType) =>
{
        ((qy < py) & (qx > px) & nonNegativeDeterminant(qx, qy, rx, ry)@(px, py))
}

qOnRight : predicate (qx:coordType, qy:coordType, rx:coordType, ry:coordType, px:coordType, py:coordType) =>
```

DRAFT -- DRAFT -- DRAFT -- DRAFT -- DRAFT -

```
{
        ((qy == py) & (qx > px) & nonNegativeDeterminant(qx, qy, rx, ry)@(px, py))
}

qAbove : predicate (qx:coordType, qy:coordType, rx:coordType, ry:coordType, px:coordType, py:coordType) =>
{
        ((qx == px) & (qy > py) & nonNegativeDeterminant(qx, qy, rx, ry)@(px, py))
}

qOnLeft : predicate (qx:coordType, qy:coordType, rx:coordType, ry:coordType, px:coordType, py:coordType) =>
{
        ((qy == py) & (qx < px) & nonNegativeDeterminant(qx, qy, rx, ry)@(px, py))
}

qBelow : predicate (qx:coordType, qy:coordType, rx:coordType, ry:coordType, px:coordType, py:coordType) =>
{
        ((qx == px) & (qy < py) & nonNegativeDeterminant(qx, qy, rx, ry)@(px, py))
}

#
#       Problem definition. This is a Boolean predicate that should
#       evaluate to 'True' when applied to any output value of the
#       function.
#
convexHull : probdef (inputPoints: list of (coordType, coordType)) -> (convexHull: list of (coordType, coordType)) =>
{
        #
        #       Given a point (px, py) on the list convexHull, there
        #       exists a point (qx, qy) in the list inputPoints (and by
        #       extension, in convexHull) such that for all points
        #       (rx, ry) on the list inputPoints, (rx, ry) is on the left
        #       or the right of the line from (px, py) to (qx, qy) (as
        #       appropriate, by quadrant of the 2D space).
        #
        given ((px, py) in convexHull)
        (
                exists ((qx, qy) in inputPoints)
                (
                        forall ((rx, ry) in inputPoints)
                        (
                                pqDiffer(qx, qy, px, py) &
                                (
                                          qOnUpperRight (qx, qy, rx, ry, px, py)
                                        | qOnUpperLeft  (qx, qy, rx, ry, px, py)
                                        | qOnLowerLeft  (qx, qy, rx, ry, px, py)
                                        | qOnLowerRight (qx, qy, rx, ry, px, py)
                                        | qOnRight      (qx, qy, rx, ry, px, py)
                                        | qAbove        (qx, qy, rx, ry, px, py)
                                        | qOnLeft       (qx, qy, rx, ry, px, py)
                                        | qBelow        (qx, qy, rx, ry, px, py)
                                )
                        )
                )
        )
}
```

6.12 Recursive list collection type

Recursive lists are lists of elements of a single type. The operations on **`list`** instances are **`head`** *(head)*, which yields single datum, the first element in the list, **`tail`** *(tail)*, which yields a list representing all but the first element of the

DRAFT -- DRAFT -- DRAFT -- DRAFT -- DRAFT -

list, and :: *(cons)*, which is used to append an element to the head of the list. Examples:

```

#       Define 'veggies' as a list of strings
veggies := list of {"carrot", "celery", "radish"};

#       'celery' will be a variable of type string initialized to the string "celery"
celery  := head tail veggies;

#       The cons (::) operator adds an item to a list
together := "rabbits" :: head veggies :: nil
```

6.13 Dynamic data structures

There are no pointers *per se* in Noisy: this restriction ensures it is always possible to partition programs by using the runtime name space as an interface between partitions.

The only new instances that can be created at runtime are new instances of functions. Functions which embody data structures can be used to achieve dynamic data structures. A point of elegance in this approach is that, in much the same way that functions may be instantiated on any hardware device on the network, the data structures embodied in functions may reside on arbitrary devices in the network. As an example, consider a data structure used to implement nodes in the abstract syntax tree of a parser, implemented as a function, where **`Node`** is a previously defined ADT:

```

node : (Node) -> (Node) =
{
        n : Node;

        iter
        {
                match
                {
                        <-node  => node <-= n;

                        node <- => n = <- node;
                }
                true    =>      ;
        }
}

createGraph : () -> () =
{
        n : Node;

        n.left = load "node";
        n.right = load "node";
}
```

Each time it is desired to dynamically create a new instance of the **`Node`** structure, a **`load`** on the **`node`** function will create a new instance of the data structure, and the executor of the statement will obtain a channel to this new instance. In a sense, this approach bundles dynamically created data structures with their own access methods (through channel reads and writes). As a result, such data structures have a transactional interface.

6.14 The `vector` type

Vectors in Noisy are not collection types, but rather are vectors in the mathematical or physics sense: geometric objects in an n-dimensional space and denote a direction.

```

```

DRAFT -- DRAFT -- DRAFT -- DRAFT -- DRAFT -

```
#       Declare a Cartesian vector
a       : vector [3] of float32;
```

DRAFT -- DRAFT -- DRAFT -- DRAFT -- DRAFT -

APPENDIX

A. A CALL-BY-VALUE LAMBDA CALCULUS WITH ERROR-TOLERANT TYPES

A central theme of the ideas presented in Noisy, is that, rather than adopting the traditional method of duplicating (or triplicating) computation in order to counteract the occurrence of failures, we introduce the concept of *error-tolerance constraints in programs*. To formalize this notion, we introduce a typed lambda calculus, λ_{ε}, in which the type ascriptions have error tolerance constraints. The role of λ_{ε} in this work is analogous to λ_{zap} in [63]. In contrast to [63], our goal is to enable programs to specify the amount of tolerable *numeric error magnitude*.

Type Inference Rules for λ_{ε}

T-Int
$$\frac{}{\Gamma \vdash n, \varepsilon : \texttt{int}, \varepsilon}$$

T-True
$$\frac{}{\Gamma \vdash \texttt{true}, \varepsilon : \texttt{bool}, \varepsilon}$$

T-False
$$\frac{}{\Gamma \vdash \texttt{false}, \varepsilon : \texttt{bool}, \varepsilon}$$

T-ConstraintPreservationUnderError
$$\frac{v : T, \varepsilon_1 \qquad K_{\varepsilon, f_t} : v \rightarrow v'}{\Gamma \vdash^{\langle t \rangle \sim f_t} v' : T, \varepsilon}$$

T-Add
$$\frac{\Gamma \vdash v : T, \varepsilon_1 \qquad \Gamma \vdash w : T, \varepsilon_2}{\Gamma \vdash v + w : T, q(\varepsilon_1, \varepsilon_2)}$$

T-If
$$\frac{\Gamma \vdash^{\langle t \rangle \sim f_t} cond : \texttt{bool}, \varepsilon \qquad \Gamma \vdash^{\langle t \rangle \sim f_t} a : T, \varepsilon_1 \qquad \Gamma \vdash^{\langle t \rangle \sim f_t} b : T, \varepsilon_2}{\Gamma \vdash^{\langle t \rangle \sim f_t} \texttt{if}\ \ cond\ \ \texttt{then}\ \ a\ \ \texttt{else}\ \ b : T, q(\varepsilon_1, \varepsilon_2)}$$

T-Abs
$$\frac{\Gamma, x : T_1, \varepsilon_1 \vdash y : T_2, \varepsilon_2}{\Gamma \vdash \lambda x : T_1, \varepsilon_1 . y : (T_1, \varepsilon_1 \rightarrow T_2, \varepsilon_2)}$$

T-App
$$\frac{\Gamma \vdash g : (T_1, \varepsilon_1 \rightarrow T_2, \varepsilon_2) \qquad \Gamma \vdash x : T_1, \varepsilon_1}{\Gamma \vdash g\ \ x : T_2, \varepsilon_2}$$

T-Let
$$\frac{v : T, \varepsilon_1 \qquad w : T, \varepsilon_2}{\texttt{let}\ \ v = w\ \ \texttt{in}\ \ e : T, r(\varepsilon_1, \varepsilon_2)}$$

The type inference rules for λ_{ε} are shown above. The first three inference rules are straightforward. For example, the value **true** with error tolerance constraint ε has type **bool**, with type error constraint ε. The fourth type inference rule, T-ConstraintPreservationUnderError is the key component that captures our proposal of error-tolerance

DRAFT -- DRAFT -- DRAFT -- DRAFT -- DRAFT -

transformations (encodings). The concept it embodies is that, if v has type T, and error tolerance constraint ε, and K_{ε,f_t} is a transformation that takes as parameters the error tolerance constraint ε and a bit upset probability distribution, f_t, and encodes v to give v', then under the occurrence of a bit upset pattern $\langle t \rangle$, which follows distribution f_t, v' obeys the type and error constraint ascriptions of v.

B. FORMAL DEFINITION OF TYPE SYSTEM

The type inference rules specify the type resulting from the combination of expressions using the language level operators.

C. IMPLEMENTATION

Figure 21 shows a screenshot of the web interface to a prototype implementation of the compiler. This interface is also available online (here).

The Noisy language grammar is listed in Appendix D. The language design is influenced most directly by the C (statement syntax) and Limbo (e.g., **`adt`** and **`list`** data type) programming languages, Hoare's CSP (channel concept) and Dijkstra's guarded commands (the **`match`** and **`matchseq`** statements), among others. Many of these influences were themselves influenced by earlier languages — Algol in the case of C, CSP, Alef and Newsqueak in the case of Limbo, etc. The overall *programming model* that Noisy provides bears some similarities to the Actors model [3]. The role of the runtime system and its associated language constructs (**`name2chan`**, **`chan2name`**, **`var2name`**) pervades the language structure. The **`name2chan`** construct enables both the facilities akin to function calls / process creation (function calls and **`spawn`** in Limbo). The **`chan2name`** and **`var2name`** language constructs were inspired by experience with the `sys->file2chan()` system library routine in the Inferno operating system [53]. The language level error, erasure and latency tolerance constraints as well as the constraint-violation driven control flow were borne out of our investigation of language-level transformations for error tolerance, and the programming language constructs which support them [58].

The process of designing the grammar was driven by the desire to attain a language structure that was relevant to our goals of ease of partitioning and error-correctness tradeoffs, as well as a desire to simplify the implementation. The grammar is LL-1 to ensure that a recursive descent parser can be built for it, using only a single token of lookahead.

The compiler implementation was heavily influenced by Niklaus Wirth's Oberon compilers. Parsing is implemented with a recursive descent parser. Unlike Wirth's compilers which generate code in a single pass, the parser is used to build a tree-based intermediate representation, an *abstract syntax tree (AST)*. The AST is an abbreviated form of the parse tree, with nodes whose presence is implicit in a given subtree removed. Our use of the AST is essentially as an intermediate representation[4]. This in-memory intermediate representation is then traversed by one of the subsequent stages. There are currently two second-stage passes that use this intermediate representation — graph output, and C code generation. The graph output pass walks the AST and symbol table data structures, and outputs it in *dot* format, which is passed to the Dot [23] tool to render the graphs in one of many formats, including Postscipt. Figures C and 23 illustrate a small example program, its AST and the associated symbol table graphs generated by the compiler and rendered with Dot.

C.1 Building the AST

The lexical analyzer converts the input source into a sequence of *tokens*, corresponding to the reserved words, operators and separators in the language, and identifiers. The parser consumes these tokens from the lexer in the process of recognizing syntactic forms. The parser is structured as a set of routines, one per grammar production. Starting with the start symbol of a program, it recursively processes each valid production at that point in the parse. The decision of which production, and hence which routine to invoke next, is driven by the grammar $FIRST(X)$ and $FOLLOW(A)$ sets. During the language design, left recursion was eliminated from the grammar using Algorithm 4.1 in [4], and the grammar was left-factored using Algorithm 4.2 in [4]. The elimination of left-recursion is important as the $FIRST(X)$ sets of two alternatives in a grammar production may overlap in the presence of left-recursion. The top-level structure of the compiler is illustrate in Figure 20.

[4] Pascal P-code was essentially a linearized form of the AST.

DRAFT -- DRAFT -- DRAFT -- DRAFT -- DRAFT -

The AST is a binary tree; when nodes in the tree have greater than two children, the children are hung off a subtree of nodes used for chaining. Among other things, nodes contain references to entries in the symbol table, and to canonical trees representing their types, if relevant.

C.2 Modifying the AST for easier code generation

There exist a few productions in the grammar which have as their result non-terminals. While this unclutters the grammar, it also leads in practice to AST subtrees that are unnecessarily "tall". For example, the grammar production for a constant delcaration is:

```
condecl                ::= "const" (intconst | realconst | boolconst) .
```

The AST subtree built for a recognized **`condecl`** production will have as its root a node with type **`condecl`**, which will have as its only child (the token **`const`** is redundant in the AST) a node with type bing one of **`intconst`**, **`realconst`** or **`boolconst`**. The subtree of height two can however be substituted directly with one of these children. For lack of a better term, we may call this "tree height shortening". Tree shortening does not affect the functionality of the AST, and it greatly simplifies the task of routines that subsequently traverse the tree to generate code or perform other actions.

C.3 The symbol table

The symbol table stores context sensitive information gleaned from the input source during the process of parsing. Its structure is simple: it is a generalized tree with each subtree corresponding to a *scope*. Linked off each node in this tree is a list of identifiers, corresponding to the identifiers defined within that scope.

C.4 Types

Types are represented in the symbol table as trees built out of the primitive types and collection type constructors. These *type trees* correspond to the parse tree of a type expression. For modules, the ordering of definition of functions does not affect the type signature, so there are multiple type trees for a given signature. In all other cases, two types are equivalent if their type trees are identical. Type equivalence is thus *structural* as opposed to *name equivalence*. To check types, the compiler performs a post-order walk of a type tree and generates a signature based on the nodes visited. Such a signature uniquely identifies a type. The graph generators include in the generated graphs textual renderings of these signatures on each node representing an identifier.

DRAFT -- DRAFT -- DRAFT -- DRAFT -- DRAFT -

D. Noisy LANGUAGE GRAMMAR

```
/*
 *      Lexical elements
 */
character               ::=     Unicode-0000h-to-Unicode-FFFFh .
rsvopseptoken           ::=     "~" | "!" | "%" | "^" | "&" | "*" | "(" | ")" | "," | "-" | "+" | "="
                                | "/" | ">" | "<" | ";" | ":" | "'" | "\"" | "{" | "}" | "[" | "]" | "|"
                                | "<-" | "." | "<=" | ">=" | "^=" | "|=" | "&=" | "%=" | "/=" | "*=" | "-="
                                | "+=" | ":=" | "!=" | ">>" | ">>=" | "<<" | "<<=" | "<-=" | "&&" | "||"
                                | "::" | "=>" | "<=>" | "==" | "++" | "--" | ">=<" .

rsvdidentifiers         ::=     "A" | "K" | "acceleration" | "adt" | "alpha" | "ampere" | "and" | "andover" |
                                "anglerate" | "bool" | "byte" | "candela" | "cardinality" | "cd" |
                                "chan" | "complex" | "const" | "crossproduct" | "current" | "dimensions" |
                                "dimparam" | "distance" | "dotproduct" | "else" | "epsilon" | "erasures" |
                                "errors" | "exists" | "false" | "fixed" | "float128" "float16" |
                                "float32" | "float4" | "float64" | "float8" | "forall" | "fourier" |
                                "function" | "given" | "head" | "highpass" | "humidity" | "if" |
                                "imaginary" | "in" | "int" | "int128" | "int16" | "int32" | "int4" |
                                "int64" | "int8" | "iter" | "kelvin" | "kg" | "kilogram" | "latency" |
                                "len" | "list" | "load" | "lowpass" | "luminosity" | "m" | "magneticflux" |
                                "mass" | "match" | "matchseq" | "material" | "meter" | "module" | "mole" |
                                "nat128" | "nat16" | "nat32" | "nat4" | "nat64" | "nat8" | "nil" | "of" |
                                "omega" | "parallel" | "predicate" | "pressure" | "probdef" | "quantize" |
                                "rational" | "real" | "return" | "reverse" | "s" | "samples" | "second" |
                                "sequence" | "set" | "sigfigs" | "signal" | "sort" | "string" | "tail" |
                                "tau" | "tderivative" | "temperature" | "time" | "timebase" |
                                "timeseries" | "tintegral" | "true" | "type" | "typeannote" | "typemax" |
                                "typemin" | "typeof" | "unionover" | "units" | "valfn" | "vector" .

zeroToNine              =       "0-9" .
onenine                 =       "1-9" .
radix                   =       onenine {zeroToNine} "r" .
charConst               =       "'" character "'" .
integerConst            ::=     ["+" | "-"] [radix] ("0" | onenine {zeroToNine}) | charConst .
boolConst               ::=     "true" | "false" .
drealConst              =       ("0" | onenine {zeroToNine}) "." {zeroToNine} .
erealConst              =       (drealConst | integerConst) ("e" | "E") integerConst .
realConst               ::=     ["+" | "-"] (drealConst | erealConst) .
numericConst            ::=     integerConst | realConst .
stringConst             ::=     "\"" {character} "\"" .
idchar                  =       char-except-rsvopseptoken .
identifier              ::=     (idchar-except-zeroToNine) {idchar} .

/*
 *      Syntactic elements: top-level program structure
 */
program                 ::=     moduleDecl {(functionDefn | problemDefn | predicateFnDefn)} .
functionDefn            ::=     identifier ":" "function" signature "->" signature "="  scopedStatementList .
problemDefn             ::=     identifier ":" "probdef" signature "->" signature "=>" scopedPredStmtList .
predicateFnDefn         ::=     identifier ":" "predicate" signature "=>" scopedPredStmtList .
signature               ::=     "(" [identifier ":" typeExpr] {"," identifier ":" typeExpr} ")" .
moduleDecl              ::=     identifier ":" "module" "(" typeParameterList ")" "{" moduleBody "}" .
moduleBody              =       {moduleTypeNameDecl ";"} .

/*
 *      Types
 */
```

DRAFT -- DRAFT -- DRAFT -- DRAFT -- DRAFT -

```
moduleTypeNameDecl      ::=     identifierList ":" (constantDecl | typeDecl | typeAnnoteDecl | functionDecl | probdefDecl | predicateFnDecl
      ) .
constantDecl            =       "const" (integerConst | realConst | boolConst) .
typeDecl                =       ("type" typeExpr) | adtTypeDecl | vectorTypeDecl .
typeAnnoteDecl          ::=     "typeannote" typeAnnoteList .
adtTypeDecl             ::=     "adt" "{" identifierList ":" typeExpr ";" {identifierList ":" typeExpr ";"} [valfnSignature ";"] "}" .
valfnSignature          =       identifier ":" "valfn" .
vectorTypeDecl          ::=     "vector" "[" integerConst "]" "of" typeExpr .
functionDecl            ::=     "function" writeTypeSignature "->" readTypeSignature .
probdefDecl             ::=     "probdef" writeTypeSignature "->" readTypeSignature .
readTypeSignature       =       signature .
writeTypeSignature      =       signature .
predicateFnDecl         ::=     "predicate" signature .
identifierOrNil         =       (identifier {fieldSelect}) | "nil" .
identifierOrNilList     =       identifierOrNil {"," identifierOrNil} .
identifierList          =       identifier {"," identifier} .
typeExpr                ::=     (basicType typeAnnoteList) | anonAggregateType | typeName .
typeAnnoteItem          =       dimensionsDesignation | unitsDesignation | signalDesignation
                                | timeseriesDesignation | sigfigDesignation | tolerance .
typeAnnoteList          =       typeAnnoteItem {"and" typeAnnoteItem} .
typeName                ::=     identifier ["->" identifier] .
dimensionsDesignation   ::=     "dimensions" dimensionArithExpr.
sigfigDesignation       ::=     "sigfigs" integerConst .
signalDesignation       ::=     "signal" (basicSignal | identifier) .
timeseriesDesignation   ::=     "timeseries" .
unitsDesignation        ::=     "units" unitsArithExpr .
dimensionArithFactor    ::=     basicSignalDimension | "(" dimensionArithExpr ")" .
dimensionArithTerm      ::=     dimensionArithFactor {highPrecedenceArith2ArithOp dimensionArithFactor} .
dimensionArithExpr      ::=     dimensionArithTerm {lowPrecedenceArith2ArithOp dimensionArithTerm} .
unitsArithFactor        ::=     (basicSignalUnits | identifier | numericConst) | "(" unitsArithExpr ")" .
unitsArithTerm          ::=     unitsArithFactor {highPrecedenceArith2ArithOp unitsArithFactor} .
unitsArithExpr          ::=     unitsArithTerm {lowPrecedenceArith2ArithOp unitsArithTerm} .
basicSignalDimension    ::=     "distance" | "mass" | "time" | "material" | "current" | "luminosity" | "temperature" .
basicSignalUnits        ::=     "m" | "kg" | "s" | "mole" | "A" | "cd" | "K" .
basicSignal             ::=     basicSignalDimension | "pressure" | "acceleration" | "magneticfluxdensity"
                                | "relativehumidity" | "anglerate" .
tolerance               ::=     errormagtolerance | losstolerance | latencytolerance .
errormagtolerance       ::=     "epsilon" "(" realConst "," realConst ")" .
losstolerance           ::=     "alpha" "(" realConst "," realConst ")" .
latencytolerance        ::=     "tau" "(" realConst "," realConst ")" .
basicType               ::=     "bool" | integerType | realType | "string" .
integerType             ::=     "nat4" | "nat8" | "nat16" | "nat32" | "nat64" | "nat128"
                                | "int4" | "int8" | "int16" | "int32" | "int64" | "int128" .
realType                ::=     "float4" | "float8" | "float16" | "float32" | "float64" | "float128" | fixedType .
fixedType               ::=     "fixed" integerConst "." integerConst .
arithmeticType          ::=     integerType | realType | fixedType | rationalType .
complexType             ::=     "complex" arithmeticType .
anonAggregateType       ::=     arraytype | listtype | tupletype | settype | rationalType | complexType .
arraytype               ::=     "array" "[" integerConst "]" {"[" integerConst "]"} "of" typeExpr .
listtype                ::=     "list" "of" typeExpr .
tupletype               ::=     "(" typeExpr {"," typeExpr} ")" .
settype                 ::=     "set" "[" integerConst "]" "of" typeExpr .
rationalType            ::=     "rational" arithmeticType .

initlist                =       "{" expression {"," expression} "}" .
idxinitlist             =       "{" element {"," element} "}" .
starinitlist            =       "{" element {"," element} ["," "*" "=>" expression] "}" .
element                 =       expression [ "=>" expression ] .

typeParameterList       =       [identifier ":" "type"] {"," identifier ":"  "type"} .
```

DRAFT -- DRAFT -- DRAFT -- DRAFT -- DRAFT -

```
valfndefn               =       identifier ":" "valfn" typeName "="  scopedStatementList .

/*
 *      Statements
 */
scopedStatementList     =       "{" statementList "}" .
statementList           =       {statement} .
statement               ::=     [ assignmentStatement | matchStatement | iterStatement | sequenceStatement
                                | parallelStatement | scopedStatementList | operatorToleranceDecl | returnStatement] ";" .
assignmentStatement     ::=     identifierOrNilList ((":" (constantDecl | typeDecl | typeExpr)) | (assignop expression))
                                | "(" identifierOrNilList ")" assignop expression .
returnStatement         ::=     "return" returnSignature .
returnSignature         =       "(" [identifier ":" expression] {"," identifier ":" expression} ")" .

operatorToleranceDecl   =       (hprecbinop | lprecbinop | unaryOp) ":" typeExpr .
assignop                ::=     "=" | "^=" | "|=" | "&=" | "%=" | "/=" | "*=" | "-=" | "+=" | ">>="
                                | "<<=" | "<-=" | ":=" .
matchStatement          ::=     ("match" | "matchseq") "{" guardedStatementList "}" .
iterStatement           ::=     "iter" "{" guardedStatementList "}" .
sequenceStatement       ::=     "sequence" (orderingHead | setHead) scopedStatementList .
parallelStatement       ::=     "parallel" setHead scopedStatementList .
setHead                 =       "(" identifier "in" expression ")" .
orderingHead            =       "(" assignmentStatement ";" expression ";" assignmentStatement ")" .
guardedStatementList    =       {expression "=>" (statementList | scopedStatementList)} .
guardedExpressionList   =       {expression "=>" expression} .


/*
 *      Expressions
 */
expression              ::=     (term {lprecbinop term}) | anonAggrCastExpr | chanevtexpr
                                | loadExpr | quantizeExpression .
quantizeExpression      ::=     identifier "quantize" "{" guardedExpressionList "}" .
listcastexpr            ::=     "list" "of" initlist .
setcastexpr             ::=     "set" "of" initlist .
arrcastexpr             ::=     "array" (("of" idxinitlist) | ("[" integerConst "]" "of" starinitlist)) .
complexCastExpr         ::=     "complex" "(" arithConst "," arithConst ")" .
rationalCastExpr        ::=     "rational" expression expression .
anonAggrCastExpr        ::=     listcastexpr | setcastexpr | arrcastexpr | complexCastExpr | rationalCastExpr .
chanevtexpr             ::=     ("erasures" | "errors" | "latency") "of" identifier cmpOp expression .
loadExpr                ::=     "load" typeExpr expression realConst .
term                    ::=     [basicType] [unaryOp] factor ["++" | "--"] {hprecbinop factor} .
factor                  ::=     (identifier {fieldSelect}) | integerConst | realConst | stringConst | boolConst
                                | "(" expression ")" | tuplevalue | namegenInvokeShorthand | typeMinExpr | typeMaxExpr
                                | namegenWriteShorthand .
namegenWriteShorthand   =       identifier "(" argumentList ")" .
argumentList            =       [identifier ":" expression {"," identifier ":" expression}] .
typeMinExpr             ::=     "typemin" "(" arithmeticType ")" .
typeMaxExpr             ::=     "typemax" "(" arithmeticType ")" .
namegenInvokeShorthand  =       identifier "(" [expression] {"," expression} ")" .
tuplevalue              ::=     "(" identifierOrNilList ")" .
fieldSelect             ::=     ("." identifier) | ("[" expression [":" expression] "]") .
hprecbinop              ::=     "*" | "/" | "%" | "^" | "::" | "lowpass" | "highpass" | "dotproduct"
                                | "crossproduct" | "centralmoment" .
lprecbinop              ::=     "+" | "-" | ">>" | "<<" | "|"  | cmpOp | booleanOp .
cmpOp                   ::=     "==" | "!=" | ">" | "<" | "<=" | ">=" .
booleanOp               ::=     "&&" | "||" .
unaryOp                 ::=     "~" | "!" | "-"  | "+" | "<-"  | "head" | "tail" | "len" | "sort" | "uncertainty"
                                | "tintegral" | "tderivative" | "timebase" | "sigfigs" | "samples" | "reverse"
                                | "fourier" | "typeof" | "cardinality" .
```

DRAFT -- DRAFT -- DRAFT -- DRAFT -- DRAFT -

```
highPrecedenceBinaryBoolOp::=   "&&" | "^" .
lowPrecedenceBinaryBoolOp ::=   "||" .
unaryBoolOp             ::=     "!" .
arith2BoolOp            ::=     "==" | "!=" | ">" | ">=" | "<" | "<=" .
highPrecedenceArith2ArithOp ::= "*" | "/" | "%" | "pow" | "nrt" | "log" .
lowPrecedenceArith2ArithOp  ::= "+" | "-" .


/*
 *      Predicate expressions, the delcarative subset of Noisy.
 */
scopedPredStmtList      ::=     "{" predStmtList "}" .
predStmtList            =       {predStmt} .
predStmt                ::=     predExpr "," .
predFactor              ::=     boolConst | identifier | "(" predExpr ")" .
predTerm                ::=     predFactor {highPrecedenceBinaryBoolOp predFactor}
                        |       predArithExpr arith2BoolOp ["@" (intParamOrConst | realParamOrConst)]
                                predArithExpr
                        |       quantifiedBoolTerm | setCmpTerm | varTuple "in"
                                ["@" (intParamOrConst | realParamOrConst)] setExpr
                        |       unaryBoolOp predFactor .
predExpr                ::=     predTerm {lowPrecedenceBinaryBoolOp predTerm} .
varIntro                ::=     identifier "in" (setExpr | typeExpr) .
varIntroList            ::=     varIntro {"," varIntro} .
varTuple                ::=     "(" identifier {"," identifier} ")" .
arithConst              ::=     intParamOrConst | realParamOrConst .
predArithFactor         ::=     arithConst | varIntro | identifier | "(" predArithExpr ")" .
predArithTerm           ::=     predArithFactor {highPrecedenceArith2ArithOp predArithFactor} .
predArithExpr           ::=     predArithTerm {lowPrecedenceArith2ArithOp predArithTerm}
                                | sumOverExpr | productOverExpr | minOverExpr | maxOverExpr .
sumOverExpr             ::=     "sum" sumProdMinMaxBody .
productOverExpr         ::=     "product" sumProdMinMaxBody .
minOverExpr             ::=     "min" sumProdMinMaxBody .
maxOverExpr             ::=     "max" sumProdMinMaxBody .
sumProdMinMaxBody       ::=     ["for" varIntro ["from" predArithExpr "to" predArithExpr]] ["with" predExpr] "of" predArithExpr .
quantifiedBoolTerm      ::=     quantifierOp varIntroList predExpr .
setCmpTerm              ::=     setExpr setCmpOp setExpr .
setFactor               ::=     constSetExpr ":" typeExpr | "{" "}" | "omega"
                        |       "(" setExpr ")" | "(" predExpr ":" typeExpr ")" .
setTerm                 ::=     setFactor {highPrecedenceBoolSetOp setFactor}
                        |       unarySetOp setFactor .
setExpr                 ::=     setTerm {lowPrecedenceBoolSetOp setTerm} .
intParamOrConst         ::=     integerConst | identifier .
realParamOrConst        ::=     realConst | identifier .
stringParamOrConst      ::=     stringConst | identifier .
baseConst               =       intParamOrConst | realParamOrConst | stringParamOrConst .
tuple                   ::=     "(" baseConst {"," baseConst} ")" .
constSetExpr            ::=     "{" tuple {"," tuple} "}"
                        |       "{" baseConst {"," baseConst} "}" .
highPrecedenceBoolSetOp ::=     "#" | "><" .
lowPrecedenceBoolSetOp  ::=     "+" | "-" | "^" | "=>" | "<=>" .
unarySetOp              ::=     "powerset" | "complement" .
quantifierOp            ::=     "forall" | "exists" | "given" .
setCmpOp                ::=     "sd" | "wd" .
```

DRAFT -- DRAFT -- DRAFT -- DRAFT -- DRAFT -

REFERENCES

[1] `http://research.microsoft.com/en-us/um/redmond /projects/z3/`. Accessed July 2011.

[2] `http://cl-informatik.uibk.ac.at/software /minismt/`. Accessed July 2011.

[3] G. Agha. An overview of actor languages. In *Proceedings of the 1986 SIGPLAN workshop on Object-oriented programming*, pages 58–67, New York, NY, USA, 1986. ACM Press.

[4] A. V. Aho, R. Sethi, and J. D. Ullman. *Compilers: Principles, Techniques, and Tools*. Addison-Wesley, Reading, Massachusetts, 1986.

[5] E. Allen, D. Chase, V. Luchangco, J.-W. Maessen, and G. L. Steele, Jr. Object-oriented units of measurement. In *Proceedings of the 19th Annual ACM SIGPLAN Conference on Object-oriented Programming, Systems, Languages, and Applications*, OOPSLA '04, pages 384–403, New York, NY, USA, 2004. ACM.

[6] T. Antoniu, P. A. Steckler, S. Krishnamurthi, E. Neuwirth, and M. Felleisen. Validating the unit correctness of spreadsheet programs. In *Proceedings of the 26th International Conference on Software Engineering*, ICSE '04, pages 439–448, Washington, DC, USA, 2004. IEEE Computer Society.

[7] M. Babout, H. Sidhoum, and L. Frecon. Ampere: a programming language for physics. *European Journal of Physics*, 11(3):163, 1990.

[8] J. Backus. Can programming be liberated from the von neumann style?: a functional style and its algebra of programs. *Commun. ACM*, 21:613–641, August 1978.

[9] A. Barea Fernández. Análisis de las prestaciones de la placa micro python board v. 1.0. 2015.

[10] J. Baylis. *Error Correcting Codes: A Mathematical Introduction*. Chapman & Hall/CRC, 1997.

[11] G. Biggs and B. A. Macdonald. A pragmatic approach to dimensional analysis for mobile robotic programming. *Auton. Robots*, 25(4):405–419, Nov. 2008.

[12] R. D. Blumofe, C. F. Joerg, B. C. Kuszmaul, C. E. Leiserson, K. H. Randall, and Y. Zhou. Cilk: An efficient multithreaded runtime system. In *Proceedings of the Fifth ACM SIGPLAN Symposium on Principles and Practice of Parallel Programming*, PPOPP '95, pages 207–216, New York, NY, USA, 1995. ACM.

[13] J. Bornholt, T. Mytkowicz, and K. S. McKinley. Uncertain: A first-order type for uncertain data. In *Proceedings of the 19th International Conference on Architectural Support for Programming Languages and Operating Systems*, ASPLOS '14, pages 51–66, New York, NY, USA, 2014. ACM.

[14] M. Broy. Declarative specification and declarative programming. In *Proceedings of the 6th international workshop on Software specification and design*, IWSSD '91, pages 2–11, Los Alamitos, CA, USA, 1991. IEEE Computer Society Press.

[15] J. Cai and R. Paige. Binding performance at language design time. In *Proceedings of the 14th ACM SIGACT-SIGPLAN symposium on Principles of programming languages*, POPL '87, pages 85–97, New York, NY, USA, 1987. ACM.

[16] K. M. Chandy and J. Misra. *Parallel program design: a foundation*. Addison-Wesley Longman Publishing Co., Inc., Boston, MA, USA, 1988.

[17] M. Chandy. Concurrent programming for the masses (invited address). In *Proceedings of the fourth annual ACM symposium on Principles of distributed computing*, PODC '85, pages 1–12, New York, NY, USA, 1985. ACM.

[18] F. Chen, G. Roşu, and R. P. Venkatesan. Rule-based analysis of dimensional safety. In *Proceedings of the 14th International Conference on Rewriting Techniques and Applications*, RTA'03, pages 197–207, Berlin, Heidelberg, 2003. Springer-Verlag.

[19] K. Clark and J. Darlington. Algorithm classification through synthesis. *The Computer Journal*, 23(1):61, 1980.

[20] R. F. Cmelik and N. H. Gehani. Dimensional analysis with c++. *IEEE Softw.*, 5(3):21–27, May 1988.

[21] A. Colmerauer and P. Roussel. The birth of prolog. In *The second ACM SIGPLAN conference on History of programming languages*, HOPL-II, pages 37–52, New York, NY, USA, 1993. ACM.

[22] E. W. Dijkstra. Guarded commands, nondeterminacy and formal derivation of programs. *Commun. ACM*, 18(8):453–457, 1975.

[23] E. R. Gansner and S. C. North. An open graph visualization system and its applications to software engineering. *Software — Practice and Experience*, 30(11):1203–1233, 2000.

[24] Go Language Developers. Go Programming Language.

[25] W. R. Harris and S. Gulwani. Spreadsheet table transformations from examples. In *Proceedings of the 32nd ACM SIGPLAN conference on Programming language design and implementation*, PLDI '11, pages 317–328, New York, NY, USA, 2011. ACM.

[26] E. C. R. Hehner. Predicative programming part i. *Commun. ACM*, 27:134–143, February 1984.

[27] E. C. R. Hehner. Predicative programming part ii. *Commun. ACM*, 27:144–151, February 1984.

[28] P. N. Hilfinger. An ada package for dimensional analysis. *ACM Trans. Program. Lang. Syst.*, 10(2):189–203, Apr. 1988.

[29] M. Hills, F. Chen, and G. RoşU. A rewriting logic approach to static checking of units of measurement in c. *Electron. Notes Theor. Comput. Sci.*, 290:51–67, Dec. 2012.

[30] C. Hoare. Viewpoint: Retrospective: an axiomatic basis for computer programming. *Commun. ACM*, 52:30–32, October 2009.

[31] C. Hoare and F. Hanna. Programs are predicates [and discussion]. *Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences*, 312(1522):475–489, 1984.

[32] C. A. R. Hoare. An axiomatic basis for computer programming. *Commun. ACM*, 12:576–580, October 1969.

[33] C. A. R. Hoare. Communicating sequential processes. *Commun. ACM*, 21(8):666–677, 1978.

[34] C. A. R. Hoare. Assertions: A personal perspective. *IEEE Ann. Hist. Comput.*, 25:14–25, April 2003.

[35] R. T. House. A proposal for an extended form of type checking of expressions. *Comput. J.*, 26(4):366–374, Nov. 1983.

DRAFT -- DRAFT -- DRAFT -- DRAFT -- DRAFT -

[36] N. Immerman. Languages that capture complexity classes. *SIAM J. Comput.*, 16:760–778, August 1987.

[37] N. Immerman. *Descriptive complexity*. Springer Verlag, 1999.

[38] S. Itzhaky, S. Gulwani, N. Immerman, and M. Sagiv. A simple inductive synthesis methodology and its applications. In *Proceedings of the ACM international conference on Object oriented programming systems languages and applications*, OOPSLA '10, pages 36–46, New York, NY, USA, 2010. ACM.

[39] JErryScript Developers. Javascript VM for Embedded devices.

[40] R. Jongerius, P. Stanley-Marbell, and H. Corporaal. Quantifying the common computational problems in contemporary applications, 2011. Unpublished draft.

[41] A. Kennedy. Dimension types. In *Proceedings of the 5th European Symposium on Programming: Programming Languages and Systems*, ESOP '94, pages 348–362, London, UK, UK, 1994. Springer-Verlag.

[42] A. Kennedy. Types for units-of-measure in f#: Invited talk. In *Proceedings of the 2008 ACM SIGPLAN Workshop on ML*, ML '08, pages 1–2, New York, NY, USA, 2008. ACM.

[43] A. J. Kennedy. Relational parametricity and units of measure. In *Proceedings of the 24th ACM SIGPLAN-SIGACT Symposium on Principles of Programming Languages*, POPL '97, pages 442–455, New York, NY, USA, 1997. ACM.

[44] B. M. Leavenoworth and J. E. Sammet. An overview of nonprocedural languages. *SIGPLAN Not.*, 9:1–12, March 1974.

[45] J. Lim, P. Stanley-Marbell, and M. Rinard. Newton Language.

[46] Malware in comments. .

[47] Motorola. Serial Peripheral Interface (SPI).

[48] NXP Semiconductors. UM10204, *I2C-bus specification and user manual*, April 2014.

[49] S. Radha and C. R. Muthukrishnan. A portable implementation of unity on von neumann machines. *Comput. Lang.*, 18:17–30, January 1993.

[50] D. M. Ritchie. The limbo programming language. *Inferno ProgrammerâĂŹs Manual*, 2, 1997.

[51] M. Rittri. Dimension inference under polymorphic recursion. In *Proceedings of the Seventh International Conference on Functional Programming Languages and Computer Architecture*, FPCA '95, pages 147–159, New York, NY, USA, 1995. ACM.

[52] J. Schwartz. Setl-a very high level language oriented to software systems prototyping. In *Proceedings of the international conference on APL*, APL '81, pages 280–, New York, NY, USA, 1981. ACM.

[53] Sean Dorward, Rob Pike, David Leo Presotto, Dennis Ritchie, Howard Trickey and P. Winterbottom. The inferno operating system. *Bell Labs Technical Journal*, 2(1):5–18, Winter 1997.

[54] A. Solar-Lezama, L. Tancau, R. Bodik, S. Seshia, and V. Saraswat. Combinatorial sketching for finite programs. In *Proceedings of the 12th international conference on Architectural support for programming languages and operating systems*, ASPLOS-XII, pages 404–415, New York, NY, USA, 2006. ACM.

[55] S. Srivastava, S. Gulwani, and J. S. Foster. From program verification to program synthesis. In *Proceedings of the 37th annual ACM SIGPLAN-SIGACT symposium on Principles of programming languages*, POPL '10, pages 313–326, New York, NY, USA, 2010. ACM.

[56] P. Stanley-Marbell. Derivation of Probability Distributions of Data Values and Error Magnitudes in Program Variables Under Single and Multi-Bit Errors and Erasures (draft).

[57] P. Stanley-Marbell, V. Estellers, and M. Rinard. Crayon: Saving power through shape and color approximation on next-generation displays. In *Proceedings of the Eleventh European Conference on Computer Systems*, EuroSys '16, pages 11:1–11:17, New York, NY, USA, 2016. ACM.

[58] P. Stanley-Marbell and D. Marculescu. A Programming Model and Language Implementation for Concurrent Failure-Prone Hardware. In *Proceedings of the Workshop on Programming Models for Ubiquitous Parallelism*, September 2006.

[59] P. Stanley-Marbell and M. Rinard. Lax: Driver interfaces for approximate sensor device access. In *15th Workshop on Hot Topics in Operating Systems (HotOS XV)*, Kartause Ittingen, Switzerland, May 2015. USENIX Association.

[60] P. Stanley-Marbell and M. Rinard. Reducing serial i/o power in error-tolerant applications by efficient lossy encoding. In *Proceedings of the 53rd Annual Design Automation Conference*, DAC '16, pages 62:1–62:6, New York, NY, USA, 2016. ACM.

[61] Z. D. Umrigar. Fully static dimensional analysis with c++. *SIGPLAN Not.*, 29(9):135–139, Sept. 1994.

[62] Unicode Consortium. *The Unicode Standard: Version 4.0*. Addison Wesley, Reading, Massachusetts, Aug. 2003.

[63] D. Walker, L. Mackey, J. Ligatti, G. Reis, and D. August. Static typing for a faulty lambda calculus. In *ACM SIGPLAN International Conference on Functional Programming*, New York, NY, USA, September 2006. ACM Press.

[64] T. Winograd. Beyond programming languages. *Commun. ACM*, 22:391–401, July 1979.

[65] P. Winterbottom. Alef language reference manual. *Plan 9 ProgrammerâĂŹs Man*, 1995.

[66] N. Wirth. What can we do about the unnecessary diversity of notation for syntactic definitions? *Commun. ACM*, 20(11):822–823, 1977.

[67] N. Wirth. *Grundlagen und Techniken des Compilerbaus*. Addison-Wesley, Bonn, 1 edition, 1996.

DRAFT -- DRAFT -- DRAFT -- DRAFT -- DRAFT -

Type Inference Rules for Operators

T-True
$$\frac{}{\texttt{true} : \texttt{bool}}$$

T-False
$$\frac{}{\texttt{false} : \texttt{bool}}$$

T-Var
$$\frac{}{x^{\tau} : \tau}$$

T-ADTmember
$$\frac{M : (\tau_1 \times \tau_2 \times \ldots \times \tau_n)}{M.k : \tau_k}$$

T-ArrayElem
$$\frac{M : (\tau \times \tau \times \ldots \times \tau)}{M[k] : \tau}$$

T-LogicalNot
$$\frac{M : \texttt{bool}}{!M : \texttt{bool}}$$

T-BitwiseNot
$$\frac{M : \tau \qquad \tau : \texttt{bool}|\texttt{nybble}|\texttt{byte}|\texttt{int}}{\sim M : \tau}$$

T-Increment
$$\frac{M : \tau \qquad \tau : \texttt{bool}|\texttt{nybble}|\texttt{byte}|\texttt{int}|\texttt{real}|\texttt{fixed}}{M\texttt{++} : \tau}$$

T-Decrement
$$\frac{M : \tau \qquad \tau : \texttt{bool}|\texttt{nybble}|\texttt{byte}|\texttt{int}|\texttt{real}|\texttt{fixed}}{M\texttt{- -} : \tau}$$

T-Head
$$\frac{M : \texttt{list of } \tau}{\texttt{hd } M : \tau}$$

T-Tail
$$\frac{M : \texttt{list of } \tau}{\texttt{tl } M : \texttt{list of } \tau}$$

T-Length
$$\frac{M : \tau \qquad \tau : \texttt{array}|\texttt{string}|\texttt{list}|\texttt{set}}{\texttt{length } M : \texttt{int}}$$

T-Name2Chan
$$\frac{M : \texttt{string}}{\texttt{name2chan } M : \texttt{chan of } \tau}$$

T-Chan2Name
$$\frac{M : \texttt{chan of } \tau}{\texttt{chan2name } M : \texttt{string}}$$

T-Var2Name
$$\frac{M : \texttt{chan of } \tau}{\texttt{var2name } M : \texttt{string}}$$

T-Multiplication
$$\frac{M_1 : \tau \qquad M_2 : \tau \qquad \tau : \texttt{bool}|\texttt{nybble}|\texttt{byte}|\texttt{int}|\texttt{fixed}|\texttt{real}}{M_1 \texttt{ * } M_2 : \tau}$$

T-Division
$$\frac{M_1 : \tau \qquad M_2 : \tau \qquad \tau : \texttt{bool}|\texttt{nybble}|\texttt{byte}|\texttt{int}|\texttt{fixed}|\texttt{real}}{M_1 \texttt{ / } M_2 : \tau}$$

T-Modulo
$$\frac{M_1 : \tau \qquad M_2 : \tau \qquad \tau : \texttt{bool}|\texttt{nybble}|\texttt{byte}|\texttt{int}|\texttt{fixed}|\texttt{real}}{M_1 \texttt{ \% } M_2 : \tau}$$

T-Add
$$\frac{M_1 : \tau \qquad M_2 : \tau \qquad \tau : \texttt{bool}|\texttt{nybble}|\texttt{byte}|\texttt{int}|\texttt{fixed}|\texttt{real}|\texttt{set}|\texttt{string}}{M_1 \texttt{ + } M_2 : \tau}$$

T-Sub
$$\frac{M_1 : \tau \qquad M_2 : \tau \qquad \tau : \texttt{bool}|\texttt{nybble}|\texttt{byte}|\texttt{int}|\texttt{fixed}|\texttt{real}|\texttt{set}}{M_1 \texttt{ - } M_2 : \tau}$$

T-Lshift
$$\frac{M_1 : \tau \qquad \tau : \texttt{nybble}|\texttt{byte}|\texttt{int}|\texttt{fixed}|\texttt{real} \qquad M_2 : \texttt{int}}{M_1 \texttt{ « } M_2 : \tau}$$

T-Rshift
$$\frac{M_1 : \tau \qquad \tau : \texttt{nybble}|\texttt{byte}|\texttt{int}|\texttt{fixed}|\texttt{real} \qquad M_2 : \texttt{int}}{M_1 \texttt{ » } M_2 : \tau}$$

T-LessThan
$$\frac{M_1 : \tau \qquad M_2 : \tau \qquad \tau : \texttt{bool}|\texttt{nybble}|\texttt{byte}|\texttt{int}|\texttt{fixed}|\texttt{real}|\texttt{string}}{M_1 \texttt{ < } M_2 : \texttt{bool}}$$

T-GreaterThan
$$\frac{M_1 : \tau \qquad M_2 : \tau \qquad \tau : \texttt{bool}|\texttt{nybble}|\texttt{byte}|\texttt{int}|\texttt{fixed}|\texttt{real}|\texttt{string}}{M_1 \texttt{ > } M_2 : \texttt{bool}}$$

T-LessThanEquals
$$\frac{M_1 : \tau \qquad M_2 : \tau \qquad \tau : \texttt{bool}|\texttt{nybble}|\texttt{byte}|\texttt{int}|\texttt{fixed}|\texttt{real}|\texttt{string}}{M_1 \texttt{ <= } M_2 : \texttt{bool}}$$

T-GreaterThanEquals
$$\frac{M_1 : \tau \qquad M_2 : \tau \qquad \tau : \texttt{bool}|\texttt{nybble}|\texttt{byte}|\texttt{int}|\texttt{fixed}|\texttt{real}|\texttt{string}}{M_1 \texttt{ >= } M_2 : \texttt{bool}}$$

Fig. 18. Type inference rules for language operators (part 1).

DRAFT -- DRAFT -- DRAFT -- DRAFT -- DRAFT -

Type Inference Rules for Operators *(continued)*

T-Equals
$$\frac{M_1 : \tau \qquad M_2 : \tau \qquad \tau : \texttt{bool}|\texttt{nybble}|\texttt{byte}|\texttt{int}|\texttt{fixed}|\texttt{real}|\texttt{string}}{M_1 \texttt{ == } M_2 : \texttt{bool}}$$

T-NotEquals
$$\frac{M_1 : \tau \qquad M_2 : \tau \qquad \tau : \texttt{bool}|\texttt{nybble}|\texttt{byte}|\texttt{int}|\texttt{fixed}|\texttt{real}|\texttt{string}}{M_1 \texttt{ != } M_2 : \texttt{bool}}$$

T-BitwiseAND
$$\frac{M_1 : \tau \qquad M_2 : \tau \qquad \tau : \texttt{bool}|\texttt{nybble}|\texttt{byte}|\texttt{int}}{M_1 \texttt{ \& } M_2 : \tau}$$

T-SetIntersection
$$\frac{M_1 : \texttt{set of } \tau \qquad M_2 : \texttt{set of } \tau}{M_1 \texttt{ \& } M_2 : \texttt{set of } \tau}$$

T-BitwiseXOR
$$\frac{M_1 : \tau \qquad M_2 : \tau \qquad \tau : \texttt{bool}|\texttt{nybble}|\texttt{byte}|\texttt{int}}{M_1 \texttt{ \^{} } M_2 : \tau}$$

T-BitwiseOR
$$\frac{M_1 : \tau \qquad M_2 : \tau \qquad \tau : \texttt{bool}|\texttt{nybble}|\texttt{byte}|\texttt{int}}{M_1 \texttt{ | } M_2 : \tau}$$

T-ListCons
$$\frac{M_1 : \tau \qquad M_2 : \texttt{list of } \tau}{M_1 \texttt{ :: } \quad M_2 : \texttt{list of } \tau}$$

T-LogicalAND
$$\frac{M_1 : \texttt{bool} \qquad M_2 : \texttt{bool}}{M_1 \texttt{ \&\& } M_2 : \texttt{bool}}$$

T-LogicalOR
$$\frac{M_1 : \texttt{bool} \qquad M_2 : \texttt{bool}}{M_1 \texttt{ || } M_2 : \texttt{bool}}$$

T-Assignment
$$\frac{M_1 : \tau \qquad M_2 : \tau}{M_1 \texttt{ = } M_2 : \tau}$$

T-DeclAssignment
$$\frac{M_1 : \tau \qquad M_2 : \tau}{M_1 \texttt{ := } M_2 : \tau}$$

T-AddAssignment
$$\frac{M_1 : \tau \qquad M_2 : \tau}{M_1 \texttt{ += } M_2 : \tau}$$

T-SubAssignment
$$\frac{M_1 : \tau \qquad M_2 : \tau}{M_1 \texttt{ -= } M_2 : \tau}$$

T-MulAssignment
$$\frac{M_1 : \tau \qquad M_2 : \tau}{M_1 \texttt{ *= } M_2 : \tau}$$

T-DivAssignment
$$\frac{M_1 : \tau \qquad M_2 : \tau}{M_1 \texttt{ /= } M_2 : \tau}$$

T-ModAssignment
$$\frac{M_1 : \tau \qquad M_2 : \tau}{M_1 \texttt{ \%= } M_2 : \tau}$$

T-ANDAssignment
$$\frac{M_1 : \tau \qquad M_2 : \tau}{M_1 \texttt{ \&= } M_2 : \tau}$$

T-ORAssignment
$$\frac{M_1 : \tau \qquad M_2 : \tau}{M_1 \texttt{ |= } M_2 : \tau}$$

T-XORAssignment
$$\frac{M_1 : \tau \qquad M_2 : \tau}{M_1 \texttt{ \^{}= } M_2 : \tau}$$

T-LshiftAssignment
$$\frac{M_1 : \tau \qquad M_2 : \tau}{M_1 \texttt{ «= } M_2 : \tau}$$

T-RshiftAssignment
$$\frac{M_1 : \tau \qquad M_2 : \tau}{M_1 \texttt{ »= } M_2 : \tau}$$

T-ChanReadToLvalue
$$\frac{M_1 : \tau_1 \qquad M_2 : \texttt{chan of } \tau_1 \qquad M_3 : \texttt{chan of } \tau_2}{M_3 \texttt{ = } M_1 \texttt{ <- } M_2 : \texttt{chan of } \tau_2}$$

T-ChanReadTest
$$\frac{M_2 : \texttt{chan of } \tau}{\texttt{<- } M_2 : \texttt{bool}}$$

T-ChanWriteTest
$$\frac{M_2 : \texttt{chan of } \tau}{M_2 \texttt{ <- } \quad : \texttt{bool}}$$

T-ChanWrite
$$\frac{M_1 : \tau_1 \qquad M_2 : \texttt{chan of } \tau_1 \qquad M_3 : \texttt{chan of } \tau_2}{M_3 \texttt{ = } M_2 \texttt{ <-= } M_1 : \texttt{chan of } \tau_2}$$

Fig. 19. Type inference rules for language operators (part 2).

DRAFT -- DRAFT -- DRAFT -- DRAFT -- DRAFT -

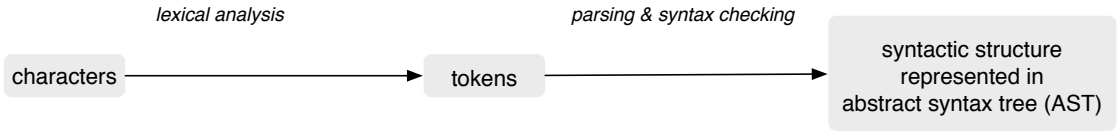


Fig. 20. Structure of the compiler.

Fig. 21. An online version of the Noisy compiler with a web-based editor allows users to explore writing Noisy programs. The online interface currently only provides a backend to view the program's AST, and does not provide a mechanism to run programs.

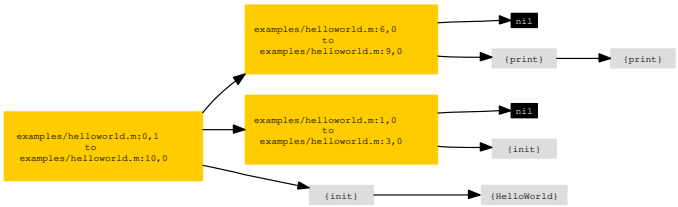
DRAFT -- DRAFT -- DRAFT -- DRAFT -- DRAFT -

```
HelloWorld : module
{
        init    : function () -> ();
}

init =
{
        print := name2chan System->print "system.print" 0.0;
        print <-= "Hello World!";
}
```

Fig. 22. An example program.

DRAFT -- DRAFT -- DRAFT -- DRAFT -- DRAFT -



(a) Symbol table state after parsing the **HelloWorld** program. The Figure is generated automatically by the compiler.

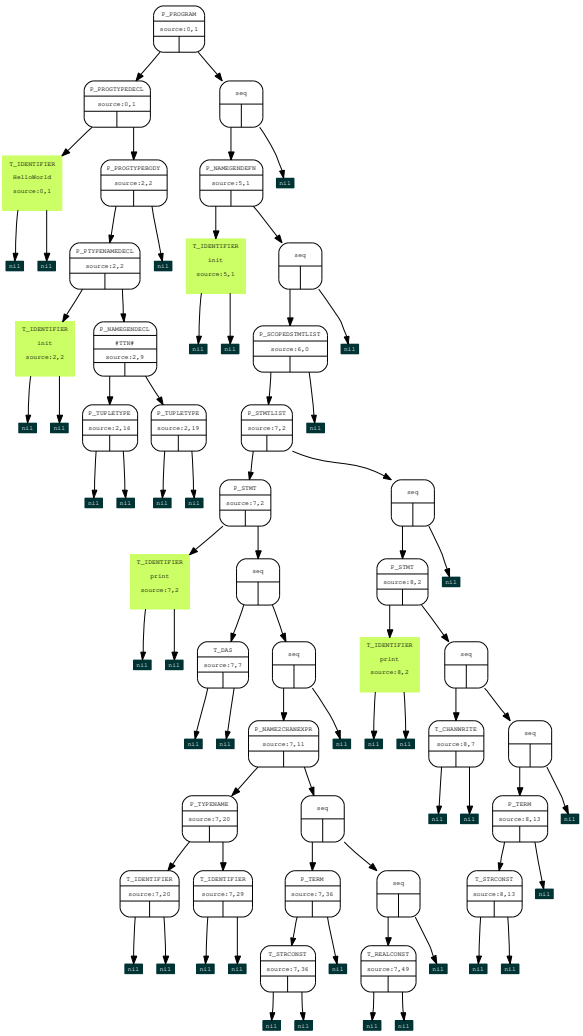


Fig. 23. Intermediate representation (Abstract Syntax Tree (AST)) of **HelloWorld** program. The Figure is generated automatically by the compiler.

DRAFT -- DRAFT -- DRAFT -- DRAFT -- DRAFT -