Noisy Language Reference, Draft Version 0.3

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Sensor-driven hardware platforms require appropriate programming abstractions. Noisy is a language designed for programming sensor-driven hardware platforms such as the Warp platform. This document describes the motivation and design of the language and provides examples of its use.

Contents

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 variously as either *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 [49] or SPI [48], most of the software for these platforms is written 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 [9] or JavaScript [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; 52; 43; 62; 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.

Most of these desirable capabilities are missing in existing languages and runtime systems. Support for these capabilities could in principle be implemented using appropriate software libraries or `pragma`s for existing embedded system programming languages such as C. Language-level constructs allow us to more succinctly describe and notate facilities such as per-variable significant figures, channels, latency, erasure, and error constraints on variables, and so on. Because presenting a language-level abstraction to the concepts enables us to present the techniques which exploit information from these constructs more succinctly, we choose to explore the new constructs we propose as a new domain-specific language. For wider deployment beyond our research goals, the techniques in Noisy could be provided as libraries for host languages such as C.

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 [46] 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.
(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.

1.1 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.

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.

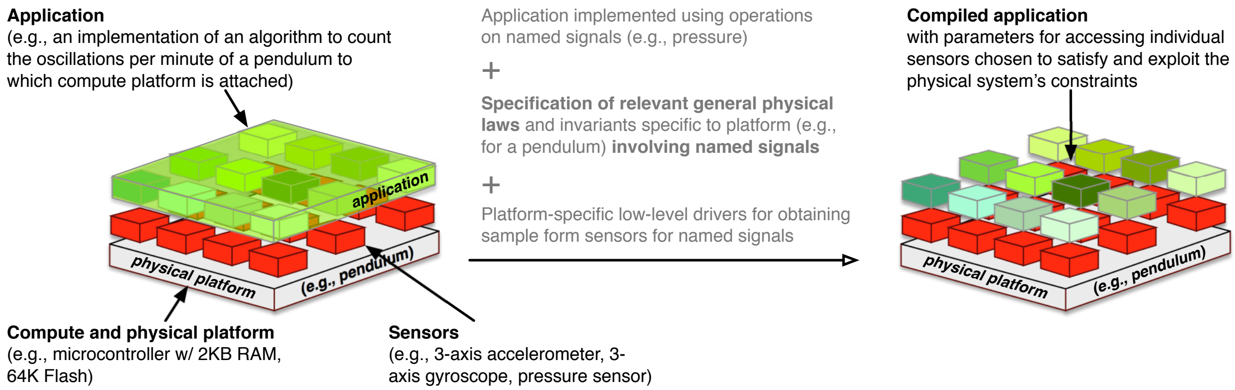

Fig. 1. Programs written in Noisy specify interaction with sensors in terms of signal types such as **`pressure`** or **`temperature`**. Hardware system designers provide physical platform descriptions written in Newton which specify general physical laws relevant to the physical system as well as specific 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, signal pressure;
```

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

1.2 Example: A pedometer application

1.3 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 $\mathrm{kilogram} \cdot \mathrm{meter}^{-1} \cdot \mathrm{second}^{-2}$ or **`kilogram meter**(-1) second**(-2)`**, where the operator `**` denotes exponentiation. 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 length. The variables **`p2`** and **`seaLevelPressure`** both have the same dimensions ($\mathrm{mass} \cdot \mathrm{length}^{-1} \cdot \mathrm{time}^{-2}$) 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, **`f`**, which takes a value **`integerArgument`** as argument and a dimension parameter **`dimensionParameter`** and returns a result **`resultValue`** with dimensions **`dimensionParameter**2`**.

1.4 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`**).

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

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

```
f : (integerArgument: int32, dimensionParameter: dimparam) -> (resultValue: dimensionParameter**2)
{
}
```

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

1.5 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.

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 [60]. 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,

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

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

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

```
pressureSample          : int32, signal pressure;
seaLevelPressure        : const 101325, units kilogram meter**(-1) second**(-2);
approximatePressure     : int32, signal pressure, 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.

or sample values to be encoded using techniques such as value-deviation-bounded serial (VDBS) encoding [61; 58] to reduce sensor I/O energy costs. Noisy's error-tolerance specification constructs are described later in this document.

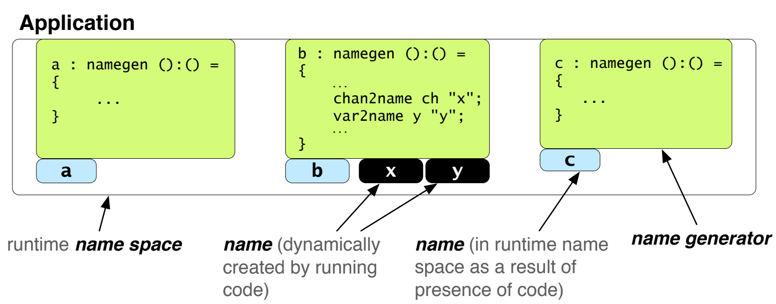

Fig. 7. Organization of applications into *namegens* which interact via *names* in a *runtime name space*, using a simple *name protocol*.

1.6 Organization of Noisy applications

Programs in Noisy are organized into units called *name generators (namegens)* (Figure 7). Name generators are collections of program statements (e.g., like functions or procedures in Algol family languages) which exchange information by explicit communication rather than transfer of control flow. They interact by communicating on *names* by which each name generator is represented in a runtime *name space*. Namegens and names are analogous to *Actors* and their *mail addresses* in the Actor system [3]. All interactions on names are expressed in terms of a small alphabet of operations, forming the *name interaction protocol*. Names abstract entries in the name space, which abstract channels, in much the same way that pointers abstract memory addresses, which abstract memory cells. Decoupling the interactions between namegens through entries in the runtime name space facilitates the easy migration of endpoints of communications. This is beneficial to application re-mapping in the presence of detected failures, for a programmable substrate with redundantly available resources.

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 ().

2.1 Hello, World

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

```
include "system.nd"

HelloWorld : progtype
{
	init	: namegen (args: list of string) -> (results: list of string);
}

init =
{
	#
	#	The first argument to the ‘name2chan‘ operator is the
	#	type of the channel that will be created. The recommended
	#	way to specify this in the case of a namegen implementation
	#	which is being loaded, is to use the ‘typeof‘ operator to
	#	get the type specified in the namegen’s progtype.
	#
	#	In this case, ‘typeof System.print‘ is the type expression
	#	‘list of string‘.
	#
	print := name2chan (typeof System->print) (string System->print);

	#
	#	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 namegen’s end
	#	achieves the same, so this is not really necessary.)
	#
	print = nil;
}
```

2.2 Pedometer

The listing below shows the implementation of a pedometer application in Noisy.

```
#
#	For the math->min and math->max namegen:
#
```

```
include "math.nd"

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

pedometer : progtype(lengthType: type, sampleType: type, countType: type)
{
        computeSteps    : namegen (windowSampleCount: lengthType, samples: sampleType, timeseries)
                                -> (count: countType);
        init            : namegen (windowSampleCount: lengthType) -> (stepsChannel: chan of countType);
}


#
#       A very simple invariant that does not even define
#       the computational problem: There cannot be more
#       steps than there are window samples.
#
init : probdef (windowSampleCount: lengthType, samples: sampleType, timeseries) -> (count: countType) =>
{
        given (windowSampleCount in lengthType)
        (
                count < windowSampleCount
        )
}


#
#       Algorithm implementation
#
computeSteps : namegen (windowSampleCount: lengthType, samples: sampleType, timeseries)
        -> (stepCount: countType) =
{
        windowMin, windowMax, windowMidPoint    : sampleType;
        stepCount                               : countType = 0;

        #
        #       Load the math module implementation (at path pathMathModule)
        #
        math := name2chan pathMathModule;

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

        windowMin = typemax(sampleType);
        windowMax = typemin(sampleType);

        foreach (s in filteredSamples)
        {
                windowMin = math->min(windowMin, s);
                windowMax = math->max(windowMax, s);
        }

        windowMidPoint = (windowMin + windowMax)/2;
        stepCount = 0;
```

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

init : namegen (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.
        #
        accelerometer           : chan of sampleType, signal acceleration, accelerometerTypeAnnote;
        accelerometerSamples    : sampleType, timeseries;

        sequence (;;)
        {
                accelerometerSamples    =<- [windowSampleCount] accelerometer;
                stepsChannel            <-= computeSteps(windowSampleCount, accelerometerSamples);
        }
}
```

2.3 Sorting

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

```
include "sortList-variantA.nd"

SelectionSort : progtype
{
        init            : namegen (args: list of string) -> (results: list of string);
        findSmallest    : namegen (stringList: list of string) -> ((string, list of string));

        sort            : namegen (inputList: list of valueType) -> (outputList: list of valueType);
        sort            : probdef (inputList: list of valueType) -> (outputList: list of valueType);
}

init (args: list of string) -> (results: list of string) =
{
        sort <- init;
        init <- sort;
}

sort : namegen (inputList: list of valueType) : (outputList: list of valueType) =
{
        #
        #       Pre-conditions: The init namegen is created, and a valid
        #               list-of-string input is written to it.
        #
        #       Post-conditions: The reader of the init namegen 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;
```

```
        findSmallestChannel     := name2chan (typeof SelectionSort->findSmallest) (string SelectionSort->findSmallest)
    ;

        rest =<- init;
        iter
        {
                #
                #       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.
                #
                len rest > 0    =>
                {
                        findSmallestChannel <-= rest;
                        (smallest, rest) =<- findSmallestChannel;
                        result = smallest :: result;
                }
        };
        sort <-= result;
}

findSmallest =
{
        #
        #       Pre-conditions: The findSmallest namegen is created, and a
        #               valid list-of-string input is written to it.
        #
        #       Post-conditions: The reader of the findSmallest  namegen
        #               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           :=<- findSmallest;
        smallest        := hd input;

        iter
        {
                #
                #       Loop invariant: 'smallest' is the lexicographically
                #               smallest item seen on input thus far, and
                #               is no smaller than any item in 'rest'.
                #
                #       Progress: in each iteration, an item is removed from
                #               'input'.
                #
                #       Termination: when input list is empty.
                #
                len input > 0   =>
                {
                        item := hd input;
                        match
                        {
```

```
                                item <= smallest =>
                                {
                                        rest = smallest :: rest;
                                        smallest = item;
                                }

                                item > smallest =>
                                {
                                        rest = item :: rest;
                                }
                        };
                        input = tl input;
                }
        };
        findSmallest <-= (smallest, rest);
}
```

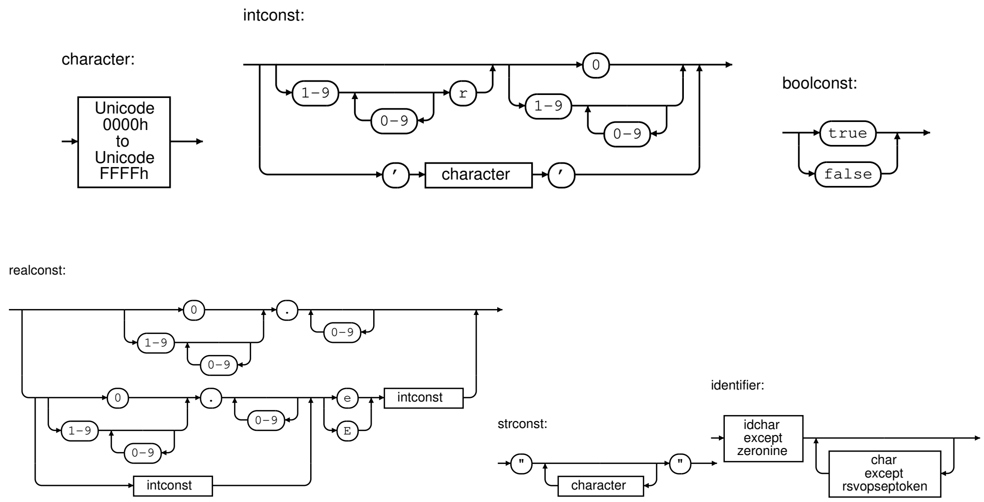

Fig. 8. Syntax diagrams for lexical elements.

3. LEXICAL ELEMENTS

Programs are sequences of Unicode [63] 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 [47].

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
chan           chan2name   const    crossproduct   current     dimensions   dimparam
```

`distance`	`dotproduct`	`else`	`epsilon`	`erasures`	`errors`	`false`
`fixed`	`float4`	`float8`	`float16`	`float32`	`float64`	`float128`
`fn`	`for`	`head`	`highpass`	`if`	`int4`	`int8`
`int16`	`int32`	`int64`	`int128`	`iter`	`kelvin`	`kilogram`
`latency`	`length`	`list`	`lowpass`	`luminosity`	`magneticflux`	`mass`
`match`	`matchseq`	`material`	`meter`	`mole`	`centralmoment`	`name2chan`
`namegen`	`nat4`	`nat8`	`nat16`	`nat32`	`nat64`	`nat128`
`nil`	`of`	`fourier`	`predicate`	`pressure`	`progtype`	`rat`
`real`	`humidity`	`imaginary`	`reverse`	`samples`	`second`	`set`
`sigfigs`	`signal`	`sort`	`string`	`tau`	`tderivative`	`temperature`
`time`	`timebase`	`timeseries`	`tintegral`	`tail`	`true`	`type`
`typeof`	`units`	`uncertainty`	`valfn`	`var2name`	`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 8.

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 [67] notation is provided in Appendix D.

4.1 Programs

A Noisy program is composed of a single program interface definition (*progtype definition*) and a collection of *name generators (namegens)*. The progtype definition specifies a set of constants, type declarations, and publicly visible namegens. All entries in the progtype definition become visible in the runtime names space.

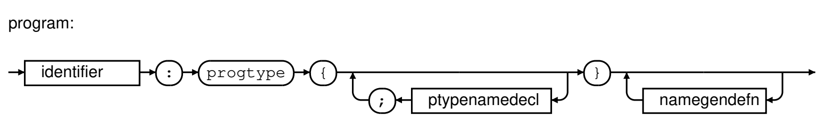

Fig. 9. Syntax diagram for overall program structure.

Example:

```
Hello : progtype
{
        init : namegen();
};
```

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 10. 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

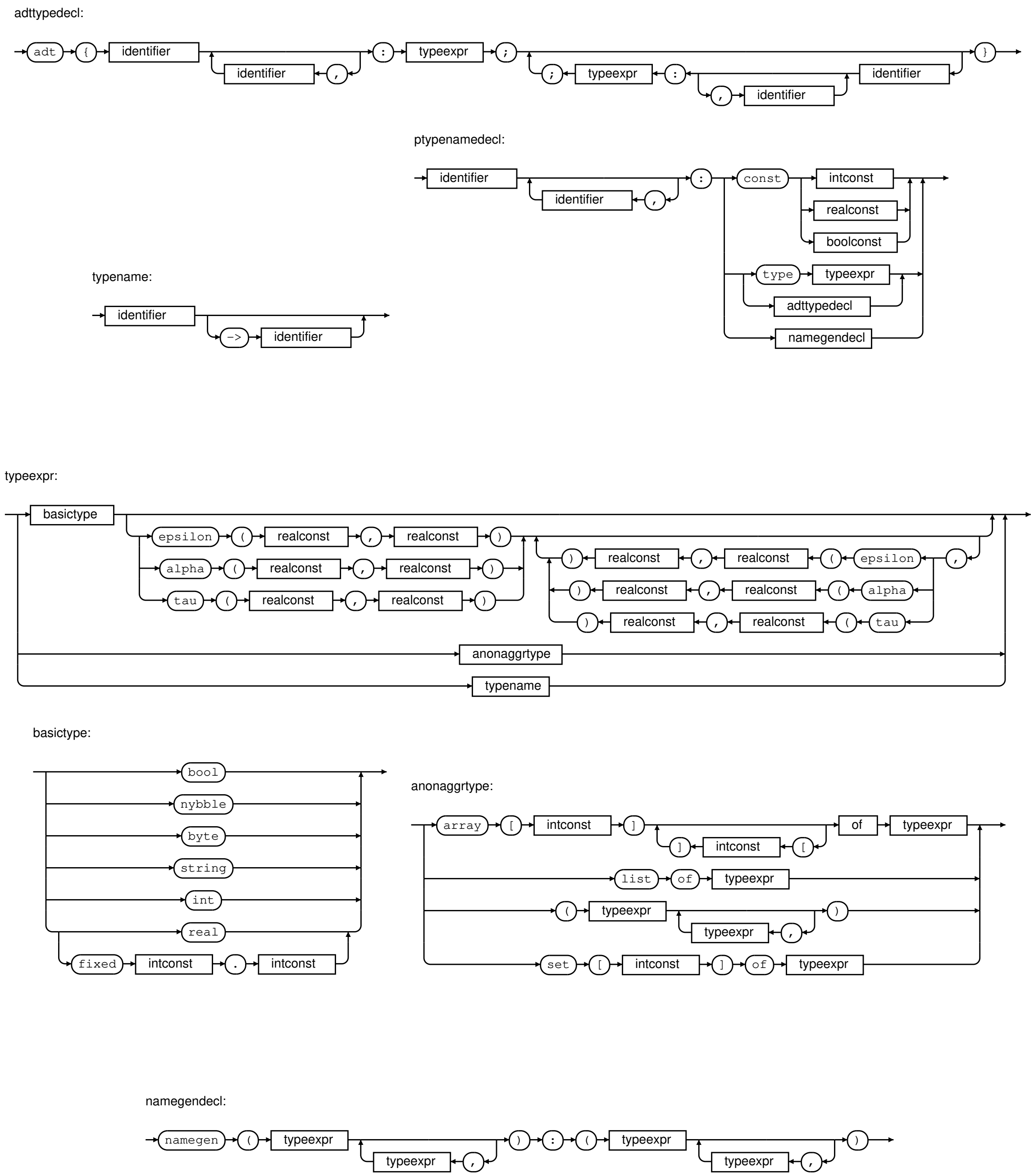

Fig. 10. Syntax diagrams for types.

(**`distance`**, **`mass`**, **`time`**, **`material`**, **`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 [57]. 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 namegens. 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 [66], Limbo [51], 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 4.9), 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* namegen 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 namegen.

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, tau(1, 0.1), 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;
```

namegendefn:

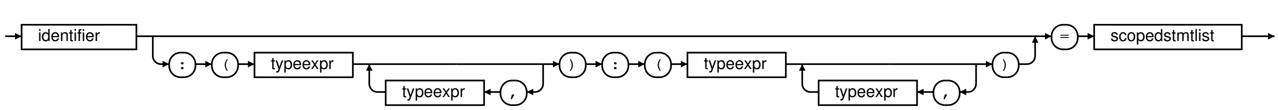

Fig. 11. Syntax diagram for name generator definition.

[1] Wirth [68] attributes the idea of sets as a language data type to Hoare, circa 1972.

4.4 Channel declarations versus channel definitions

Programs use channels to communicate between two namegens. Before a program can use a channel, it must associate it with a name in the runtime name space via a **name2chan** expression. A channel declaration only serves to ascribe a type to the identifier that will eventually refer to a name in the runtime name space. A channel **definition** is the association of a name in the runtime to a channel identifier, i.e., assigning the result of a **name2chan** to an identifier — prior to a definition, channel identifiers have the value `nil`.

4.5 Structuring programs

Programs are composed of *program types (progtypes)* and their implementations, a collection of *name generators (namegens)*. A progtype is a unit of modularity that defines a set of types, constants, and name generators. The unit of compilation of programs is a single progtype 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 namegens. Due to the structure of the language and its runtime system, it is however possible to further partition a single namegen into smaller pieces.

A *name generator* or *namegen* 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 namegens. Namegens are not functions: i.e., control flow does not pass between namegens. A namegen may bind a channel variable to a *name*. Syntactically, names are represented by strings. Such strings are part of a runtime *name space*[2]. The syntax diagrams for the grammar production for a valid namegen definition is shown in Figure 11.

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

```
Math : progtype
{
	sqrt	: namegen (float32) -> (float32);
	exp	: namegen (float32, float32) -> (float32);
}

#	The actual implementation of the Math progtype must have
#	definitions for the namegen types sqrt and exp:
sqrt =
{
}

exp =
{
}

#	A namegen that does not appear in the interface is declared
#	and implemented in one step here
somefunc : (float32, float32) -> (float32) =
{
	#	Declaration of 'sqrt' in progtype introduced a new type name.
	#	We use that as the type of the variable bound to the namegen sqrt:
	s := name2chan sqrt "sqrt";
}
```

The definition of a namegen in a progtype introduces a new type name made up of a *write type* and a *read type*, that can be used in a name2chan expression. If a namegen is not defined in its progtype declaration, it is not visible within the name space once the progtype implementation is loaded. However, the definition of the namegen within the body of the program introduces a new type, as it would if it had been declared in the progtype. Within the body of a namegen, the namegen's name is a channel

[2]By analogy, a computing system fashioned on the von Neumann model has the concept of *memory addresses* which are represented by integers, and are part of an *address space*.

which when read from has the namegens *read type*, and which for the purposes of writes, has the namegen's *write type*. Applying the **`name2chan`** operator to a name that has type **`namegen`** causes the instantiation of a new thread of control / instance of the namegen. Example:

```
#       Defines a namegen mul.  An entry in the name space "mul"
#       with write type (int16, int16) and read type (int16) will exist
#       at runtime

mul : (int16, int16) -> (int16) =
{
}
```

4.6 Scopes

The largest scope is the body of a namegen; there is no global scope. Within a namegen, 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:

- **`progtypebody`** production
- body of ADT type declaration
- **`scopedstmtlist`** production
- **`guardedscopelist`** production

The complete language grammar is provided in Appendix D.

4.7 Statements

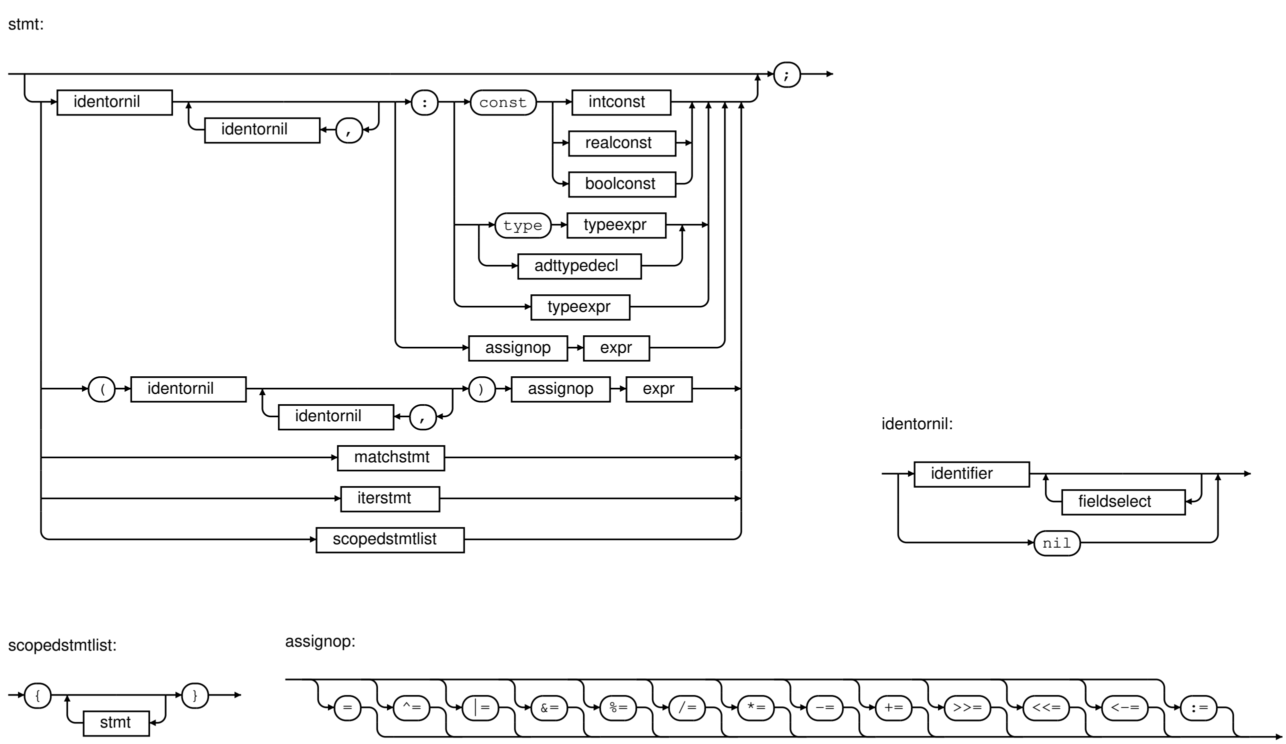

Fig. 12. Syntax diagrams for statements

The statements which make up the body of a namegen define how it computes, creates names in the runtime name space, and communicates with other namegens. Figure 12 shows the syntax diagrams for grammar productions corresponding to valid statements.

4.8 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 12 illustrates the syntax diagrams for the associated grammar productions. Example:

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

4.9 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 *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 13 illustrates the grammar productions. Section 5 discusses operators in more detail.

4.10 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 14 illustrates the syntax of **match** and **matchseq** statements with syntax diagrams.

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 namegen:

```
fibonacci : progtype
{
	fib : namegen (input: int16) -> (result: int16);
}

fib : (input: int16) -> (result: int16) =
{
	#
	#	Reading the namegenerator 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
	{
```

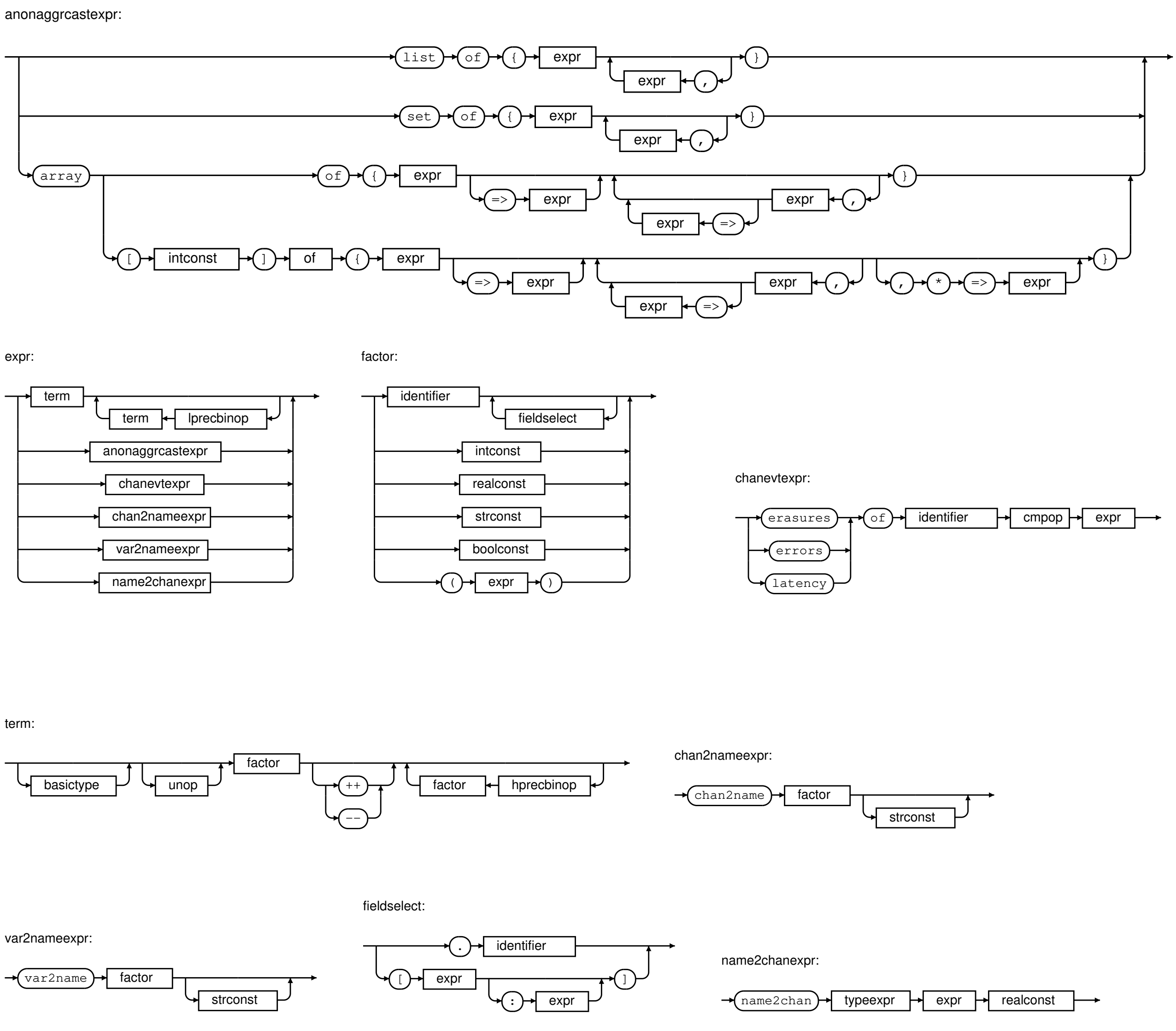

Fig. 13. Syntax diagrams for expressions

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

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

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

matchstmt:

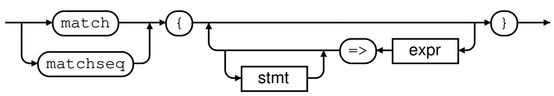

Fig. 14. Syntax diagrams for match statements

```
				r <-= <-c1 + <-c2;
			}
		};
}
```

Another implementation of a Fibonacci sequence generator namegen:

```
parfib : (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).

4.11 The **if else** construct

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

4.12 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 15.

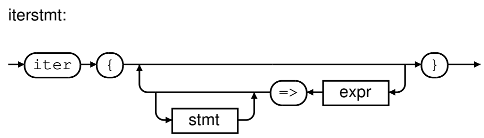

Fig. 15. Syntax diagrams for **iter** statements

4.13 The **sequence** and **foreach** construct

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

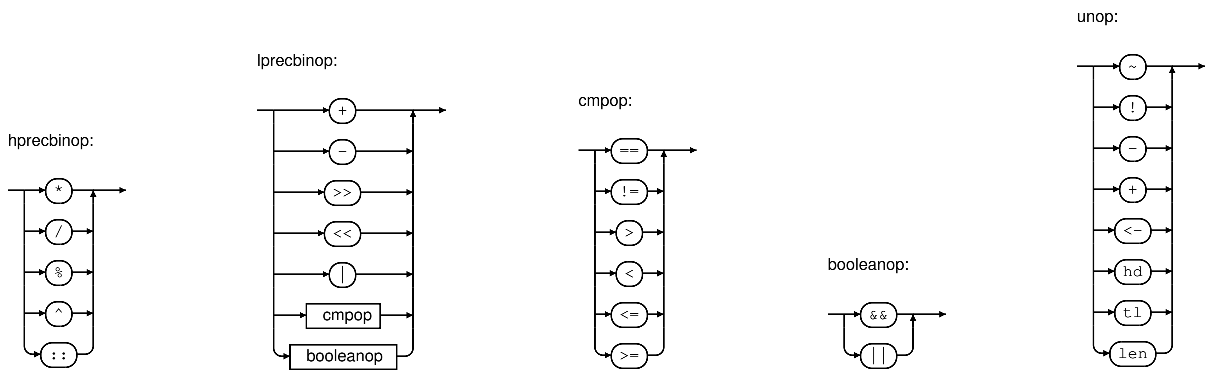

Fig. 16. Syntax diagrams for operators, and their classifications.

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 16.

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[3].

5.1 Operators on names

The operators on names are **name2chan**, **chan2name**, and **var2name**. The **name2chan** operator applied to a name (string constant) yields a channel to an entry in the name space having the same type as the *l-value* of the statement, i.e., it matches on both the name as well as type of an entry in the runtime name space. If the name corresponds to a namegen, a new instance of the namegen is created, as described in Section 7. If multiple matches exist, the match is non-deterministic. A **name2chan** expression completes as soon as it either succeeds or times out. If no match exists (timed out), the result of the **name2chan** expression is **nil**. Example:

```
#       Bind channel 'c' to the name "Fibonacci" having
#       type FibonacciType, timeout after 4 seconds
c       := name2chan FibonacciType "Fibonacci" 4E6;
```

New entries in the runtime name space can be synthesized as interfaces to channels or variables within a namegen, via the **chan2name** and **var2name** operators. If there is an extant entry in the name space of the parent progtype with the same name

[3]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.

Table 1. Noisy language operators.

Operator	Description	Operator	Description
`.`	ADT member access	`=`	Assignment
`[]`	Array or character string subscript	`:=`	Declaration and assignment
`]`*arg*`[`	Obtain dimensions of *arg*	`+=`	Addition/concatenation/union assignment
`}`*arg*`{`	obtain units of *arg*	`-=`	Subtraction/difference and assignment
`>`*arg*`<`	obtain relative uncertainty of *arg*	`*=`	Multiplication and assignment
`!`	Logical not	`/=`	Division and assignment
`~`	Bitwise not	`%=`	Modulo and assignment
`++`	Increment	`&=`	Bitwise AND and assignment
`--`	Decrement	`|=`	Bitwise OR and assignment
name2chan	Bind name in name space to channel	`^=`	Bitwise XOR and assignment
chan2name	Make channel visible as name in name space	`«=`	Logical left shift and assignment
var2name	Make variable visible as a name in name space	`»=`	Logical right shift and assignment
type	Type cast	`<-`	Assignment to/from channel
`*`, `/`, `%`	Multiplication, division, modulo	**head**	List head value
`+`	Unary plus, addition, set union,	**tail**	List tail value
	string concatenation	**length**	List, array, or string length; set size
`-`	Unary minus, subtraction, set difference	**sort**	List, array, or string length; sort by **valfn**
`«`	Logical left shift	**reverse**	List, array, or string length; reverse by **valfn**
`»`	Logical right shift	**tintegral**	Integral over time of a **timeseries** variable
`**`	Exponentiation	**tderivative**	Derivative with respect to time of a **timeseries**
`<`	Less than	**fourier**	Compute the discrete Fourier transform of a **timeseries**
`>`	Greater than	**timebase**	Obtain sampling time indices of a **timeseries**
`<=`	Less than or equal to	**samples**	Obtain sample data from a **timeseries**
`>=`	Greater than or equal to	**uncertainty**	Obtain posterior distribution of uncertainty for a **signal**
`==`	Equals	**centralmoment**	Compute the nth central moment of a distribution
`!=`	Not equals	**lowpass**	Low-pass filter a **timeseries**
`>=<`	Is permutation of	**highpass**	High-pass filter a **timeseries**
`&`	Bitwise AND, set intersection	**sigfigs**	Obtain number of significant figures of a **signal**
`^`	Bitwise XOR	**dotproduct**	Compute the inner product of two **vector** variables
`|`	Bitwise OR	**crossproduct**	Compute the vector product of two **vector** variables
`::`	List append	**typemin**	Give the maximum value that an arithmetic type can take
`&&`	Logical AND	**typemax**	Give the minimum value that an arithmetic type can take
`||`	Logical OR	`=>`	Implication (a binary infix operator)

and type, it is replaced with the new entry, but only within the scope of the initiating namegen and namegens which it has instantiated via `name2chan`. When a variable which has been made visible in the name space via **var2name** is written to, the write not only updates the memory cell on the local device, but also generates a write to any channel bound to the name.

5.2 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 namegens is over a channel. Since namegens 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. Instead, the reference must be converted to a name via chan2name. The value of chan2name and var2name expressions is the name (type **string**) that was posted for the chan, or `nil` if the posting failed. The chan2name and var2name operators can either be used to post an explicitly chosen name, e.g.,

```
chan2name mychan "name";
```

or might be used to generate an implicit name, in which case the name posted is chosen by the runtime and returned as the values of the **chan2name** or **var2name** expression.

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**, nat4, **nat8**, **int32**, **fixed** (fixed-point approximate real numbers), **float32** (floating-point approximate real numbers), **rat** (rational numbers), and **string**. The arithmetic types are **bool**, **nat4**, **nat8**, **int32**, **fixed** and **float32**, and **rat**. The basic language data types may be employed in 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 **progtype**, **namegen** or act as an alias for a type expression. In the cases of progtypes and namegens, the type signatures are functions of the body of the progtype definition, and that of the namegen 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 namegen 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 [57] to implement forward error correction on the values exchanged between namegens. 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[4].

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 namegens). 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**, **int32**, **float32** and **fixed**

The primitive types **bool**, **nat4** and **nat8** are unsigned quantities with sizes 1, 4 and 8 bits respectively. The type **int32** is a signed 32-bit value in two’s complement format. The fixed point approximate real numbers, **fixed**, are signed 16-bit binary fixed point values in which 0 up to 15 bits can be used to represent the fractional component, and one bit is used to represent the sign. The floating point approximate real numbers, **float32** are in 64-bit IEEE-754 double precision floating point format.

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 **len** 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[len "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 **len** 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:

[4]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].

```
#       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, 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 namegen solves, using **`probdef`** definitions. Noisy **`probdef`** definitions use logic to specify relationships (predicates) that must hold between the namegens 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 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 (∀, ∃) 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 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 [56]. 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; 65], 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 [50]. Expressions in L_1 [15], a subset of SETL [53] 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 [55] 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. [56] 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 namegens

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

#
#
#
DFT : progtype (sampleType: type, indexType: type)
{
	dft	: namegen (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 namegen
	#
	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

```
#
#       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
#
#                       | 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.
#
ConvexHull : progtype (coordinateType: type)
{
        convexHull              : namegen       (inputPoints: list of (coordinateType, coordinateType)) -> (convexHull
    : list of (coordinateType, coordinateType));
        convexHull              : probdef       (inputPoints: list of (coordinateType, coordinateType)) -> (convexHull
    : list of (coordinateType, coordinateType));

        pqDiffer                : predicate     (qx:coordinateType, qy:coordinateType) @ (px:coordinateType, py:
    coordinateType);

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



#
#       Several predicate functions for the eventual problem definition
#
pqDiffer : predicate (qx:coordinateType, qy:coordinateType) @ (px:coordinateType, py:coordinateType) =
{
```

```
        !((qy == py) & (qx == px))
}

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

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

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

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

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

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

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

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

qBelow : predicate (qx:coordinateType, qy:coordinateType, rx:coordinateType, ry:coordinateType) @ (px:coordinateType, py:coordinateType) =>
{
        ((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
#       namegen.
#
convexHull : probdef (inputPoints: list of (coordinateType, coordinateType)) -> (convexHull: list of (coordinateType,
     coordinateType)) =>
{
        #
        #       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, **`tl`** *(tail)*, which yields a list representing all but the first element of the 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 namegens. Namegens 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 namegens may be instantiated on any hardware device on the network, the data structures embodied in namegens 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 namegen, 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 = name2chan "node";
	n.right = name2chan "node";
}
```

Each time it is desired to dynamically create a new instance of the **Node** structure, a **name2chan** on the **node** namegen 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.

```

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

7. THE RUNTIME SYSTEM

One way to look at the runtime system is by analogy to the memory system in a stored program computer. In traditional models of a stored program computer (e.g., the von Neumann / Princeton model), programs access *memory cells* by performing operations on *addresses*. These addresses form an *address space*. Two operations can be performed on a memory cell, given an address that represents it: memory read and memory write. When programs in a language such as C allocate memory dynamically, they are essentially communicating with the operating system to obtain a new address. We could call this operation on the address space new address, although it doesn't really *introduce* a new address, but just provides access to the address, to a program. We can thus say that the alphabet of operations on memories is {memory read, memory write, new address}. In a computer system, these operations are manifest as operations in hardware: a memread operation is embodied in instructions in the machine's instruction set architecture which perform a read from memory, e.g., an **ld** (load) instruction. Furthermore, the execution of such an instruction leads to a communication between the processor and the memory, yielding the result of the load.

By analogy, the runtime system in Noisy is made up of *names*, which are accessed through *channels*. The alphabet of operations pertinent to names is {nameread, namewrite, name2chan, chan2name, var2name}. The name2chan operation obtains a new channel through which programs can write to an entry in the name space. Conversely, chan2name (var2name) makes a channel (variable) in a program visible as an entry in the name space. Entries in the name space have the type structure of the variables or channels with which they are associated. As an example, a nameread operation is logically associated with a channel read expression in a program, just as a memread in the discussion above is logically associated with reading the value of a variable. Just as a memread leads to a communication on the address and data buses to memory, a nameread causes a device on which a namegen is executing to communicate with other computing devices which are part of the name space. It is at the level of these messages that error, loss (erasure) and latency tolerance constraints for channels are used to drive encoding. It is also from the framework implementing these low level messages that the tolerance constraint violations on channels are obtained. The nature and protocol of these communications is the subject of Section 7.4.4.

7.1 Target hardware model

The underlying hardware *abstraction* is assumed to be a collection of computing devices. More concretely, it is assumed that each namegen is mapped onto a *virtual processing device*, and the virtual processing devices are interconnected via a single *virtual network*. The virtual processing devices might have a one-to-one or many-to-one correspondence with actual processing devices (e.g., microcontrollers, processor cores, microprocessors, workstations). Similarly, the virtual network might be composed of a multi-hop wired or wireless network, on-chip bus, on-chip network, etc. The virtual processing devices will subsequently be referred to as *processing devices*, and the virtual network as *the network*, without discussing further details of either the nature of processing devices, or issues such as the underlying implementation of device-to-device communication, routing within the network, or optimization of placement/mapping of namegens to actual physical processing devices. The combination of virtual processing devices and the virtual network will be referred to collectively as the *runtime system*. The term *loading a program* will subsequently be used to refer to the act of placing the compiled Noisy program on a virtual device. It should be stressed that the above statements describe an *abstraction*; their purpose is to enable a description of the system without getting mired in implementation-specific details.

7.2 Structure of the runtime name space

All namegens exposed in an application's progtype definition appear as entries in the runtime name space with names of the form *progtype.namegen*. Entries in the runtime name space with distinct types associated with them are distinct. Duplicate entries (with identical names and types) may exist; this introduces nondeterminism.

A namegen is only *executing*, after its interface name has been bound to a channel. Each binding of a name to a channel creates a logically new instance of the namegen. Such a namegen instance so created shares the same name space as the namegen that bound its interface to a channel, and any changes to the runtime name space (e.g., creation of new entries via **`chan2name`** or **`var2name`**) are mutually visible. Besides entries corresponding to namegens, namegens may dynamically create entries in the runtime name space tied to channels. Such entries have the form *progtype.namegen.name*.

7.3 Enforcing access restrictions on names

The channels used by namegens to access names, can be used to implement the concept of *capabilities* from capability-based systems [45]. They provide an access path to software or hardware that is represented by a name in the name space. Access control can trivially be implemented by requiring the first value written down a channel to be an access right (e.g., a password)[5].

7.4 Runtime system implementation

The *runtime system* is the collection of data structures, instantiated at runtime, that support the underlying operations being performed by executing programs. At the heart of the runtime system implementation is a set of three tables: the *name table*, *activation record table* and the *chan table*, illustrated in Figure 17. The implementation of

[5]Furthermore, a particular application might even define the sequence of accesses that must precede "real" interaction, to engage the accessor in, say, a Diffie-Hellman key generation, generating a shared secret that can be used to encrypt subsequent communications.

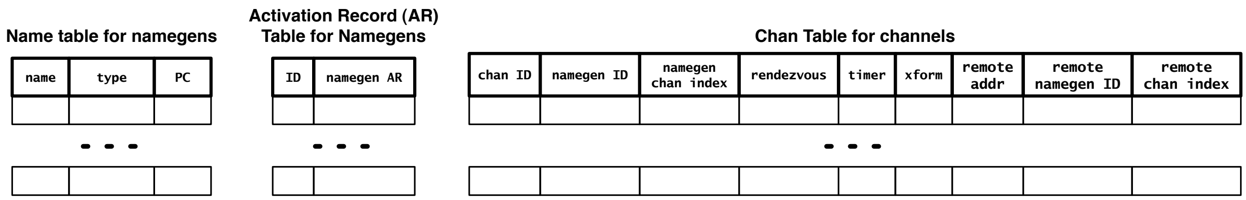

Fig. 17. Structures underlying the implementation of the runtime system.

these tables is described in Section 7.4.1.

7.4.1 *The name table.* The name table contains an entry for each namegen installed on a device, along with an entry representing the type structure of the namegen. The **Name** entries are strings representing the namegen, qualified by the progtype of which they are part (entries in the runtime name space are of the form *progtype.namegen[.name]*). At runtime, new entries are added to the name table whenever an executing namegen performs a **chan2name** or **var2name** operation. New entries in the name table are created whenever new code is installed on a device. By convention, a namegen with the identifier **init** immediately begins executing once loaded. Loading a namegen implementation with the same progtype as an extant one, into the runtime system (e.g., on a different device) should be thought of as being the same as overwriting code memory of a running application in a traditional program; undefined behavior will result.

When a namegen performs a **name2chan** operation, the local name table is first consulted. If no matching name and type is found locally, the name tables of all devices in the network are consulted[6]. If such an operation is successful, i.e., the name and type match an entry in the local name table, a new instance of the namegen (based on the **PC** entry) begins executing, with its own private stack. Such an instance is termed a namegen *activation*. The state for currently instantiated namegens is maintained in the *activation record table*.

7.4.2 *The activation record table.* The activation record table maintains the state corresponding to each namegen instantiation (as created by a **name2chan**, or an **init** namegen (Section 7.4.1)). The **ID** field uniquely identifies an instantiated namegen, and is used to identify namegens for all other operations. For example, all channels are associated with a particular namegen instance, and the instance's *ID* is used to track this correspondence. An instantiation of a namegen may create new entries in the runtime name space; these are only visible to the namegen that caused their instantiation (and to themselves).

7.4.3 *The chan table.* The chan table contains entries for all channels that are within the current scope of execution of all namegen activations. A namegen that performs a send or receive operation on a channel sleeps on a *rendezvous structure* in the chan table. When the channel communication operation completes (e.g., message successfully transmitted over network and an acknowledgment received), the sleeping namegen is awoken. The **xform** field contains a matrix (logically a part of the channel's type) representing the linear transformations that must be used to encode and decode the data exchanged between devices, representing the communication on a language-level channel. The messages on the network which are generated as a result of operations on channels are described in the next Section.

7.4.4 *Name communication protocol.* A small alphabet of messages may be exchanged between devices as a result of language-level constructs related to channels. The list of messages in this alphabet is provided in Table 2. The following detail the effect of the receipt of messages in Table 2, on the runtime table structures, and on execution at the recipient node. The only language level channel operators that do not lead to the generation of messages are chan2name and **var2name**. They lead only to the creation of entries in the local name table.

Tname2chan / Rname2chan. Execution of a **name2chan** expression in a namegen will initiate the generation of a Tname2chan message on the network. A device which contains a matching entry (on both name and type) in its

[6]Logically, the query is a broadcast, but an implementation may perform any number of optimizations to make this lookup more efficient.

Table 2. Name communication protocol.

Message	Description	Associated Language Construct	Parameters
Tname2chan Rname2chan	Bind name to channel; if name is a namegen, create instance Response: chan ID or nil	**`name2chan`**	name, type
Tnameread Rnameread	Channel receive Response: type structured data	Channel receive expression (`<-c`)	chan ID
Tnamewrite Rnamewrite	Channel send Acknowledgment	Channel send expression (`c <-= `)	data, chan ID

name table responds with a Rname2chan message. It is possible that no such device might exist, in which case the language-level expression will evaluate to **`nil`** after the language-level-specified timeout.

If the supplied name, in the name space, is a namegen, a new activation of the remote namegen is created, and corresponding entries for the send / receive interface channel tuple in the remote device's chan table are created. The ID of this allocated entry is returned to the initiating node in a **`Rname2chan`** message. A new entry is created in a local *chan table*, and this entry is used to store the received tag. Subsequent operations on the channel associated with this **`name2chan`** operation will occur with the specific instantiation of the remote namegen.

Tnamewrite / Rnamewrite. A channel send operation causes a Tnamewrite message to be generated on the network. The message target is determined by a lookup in the local chan table for (1) the destination network address and (2) the destination namegen **`ID`**, and (3) the destination namegen channel index, which identifies a channel in a specific instance of the remote namegen (with its private execution stack) that the values should be delivered to. The **`timer`** entry of the local chan table is updated with a timestamp, which is used to determine timeouts when the channel appears in a latency violation expression.

Tnameread / Rnameread. A channel receive operation causes a Tnameread message to be generated on the network. A lookup is performed in the local chan table to determine the remote device and the ID, to be included in the **`Tnameread`** message, designating which channel in a specific instantiation of a remote namegen the message should be delivered to. The **`timer`** entry of the local chan table is updated with a timestamp, which is used to determine timeouts when the channel appears in a latency violation expression.

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 [64]. In contrast to [64], 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
$$\frac{v : T_1, \varepsilon_1 \qquad K_{\varepsilon, f_t} : v \to v'}{\Gamma \vdash^{\langle t \rangle \sim f_t} v' : T, \varepsilon}$$

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

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

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

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

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 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 [54]. 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 [59].

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[7]. 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.

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

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 progtypes, the ordering of definition of namegens 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.

D. Noisy LANGUAGE GRAMMAR

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

***** TODO: check where each of these is used in grammar

rsvdidentifiers         ::=     "A", "acceleration", "adt", "alpha", "K", "ampere", "andover",
                                "anglerate", "bool", "byte", "candela", "cardinality", "cd", "chan", "chan2name",
                                "complex", "const", "crossproduct", "current", "dimensions",
                                "dimparam", "distance", "dotproduct", "else", "epsilon", "erasures",
                                "errors", "false", "fixed", "float128" "float16", "float32",
                                "float4", "float64", "float8", "fn", "foreach", "given", "head",
                                "highpass", "if", "imaginary", "int", "int128", "int16", "int32", "int4",
                                "int64", "int8", "iter", "kelvin", "kg", "kilogram", "latency",
                                "len", "list", "lowpass", "luminosity", "m", "magneticflux", "mass",
                                "match", "matchseq", "material", "meter", "mole", "name2chan",
                                "namegen", "nat128", "nat16", "nat32", "nat4", "nat64", "nat8",
                                "nil", "of", "omega", "fourier", "predicate", "pressure",
                                "progtype", "rat", "real", "humidity", "reverse", "s", "samples",
                                "second", "sequence", "set", "sigfigs", "signal", "sort", "string",
                                "tau", "tderivative", "temperature", "time", "timebase",
                                "timeseries", "tintegral", "tail", "true", "type", "typeof", "typeannote",
                                "typemin", "typemax", "unionover", "units", "valfn", "var2name",
                                "vector" .

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

/*
 *      Syntactic elements
 */
program                 ::=     progtypedecl {(namegendefn | problemdefn | predicatefndefn)} .
progtypedecl            =       identifier ":" "progtype" "(" typeParameterList ")" "{" progtypebody "}" .
progtypebody            =       {ptypenamedecl ";"} .
ptypenamedecl           ::=     identlist ":" (condecl | typedecl | namegendecl | probdefdecl | predicatefndecl) .
condecl                 =       "const" (integerConst | realConst | boolConst) .
typedecl                =       ("type" typeExpr) | adttypedecl | vectortypedecl .
typeAnnoteDecl          ::=     "typeannote" typeAnnoteList .
adttypedecl             ::=     "adt" "{" identlist ":" typeExpr ";" {identlist ":" typeExpr ";"} [valfnsignature ";"]
      "}" .
valfndefn               =       identifier ":" "valfn" .
```

```
vectortypedecl          ::=     "vector" "[" integerConst "]" of typeExpr .
namegendecl             ::=     "namegen" writeTypeSignature "->" readTypeSignature .
probdefdecl             ::=     "probdef" writeTypeSignature "->" readTypeSignature .
readTypeSignature       =       signature .
writeTypeSignature      =       signature .
predicatefndecl         ::=     "predicate" boundVariablesSignature "@" freeVariablesSignature .
boundVariablesSignature =       signature .
freeVariablesSignature  =       signature .
identornil              ::=     (identifier {fieldselect}) | "nil" .
identornillist          =       identornil {"," identornil} .
identlist               =       identifier {"," identifier} .
typeExpr                ::=     (basictype typeAnnoteList) | anonaggrtype | typename .

***** TODO: this needs to be cleaned up.....
typeAnnoteList          ::=     [dimensionsDesignation]
                                ["," unitsDesignation]
                                ["," signalDesignation]
                                ["," timeseriesDesignation]
                                ["," sigfigDesignation]
                                ["," tolerance {"," tolerance}] .
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 .
anonaggrtype            ::=     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                =       "{" expr {"," expr} "}" .
idxinitlist             =       "{" element {"," element} "}" .
starinitlist            =       "{" element {"," element} ["," "*" "=>" expr] "}" .
element                 =       expr [ "=>" expr ] .
signature               ::=     "(" [identifier ":" typeExpr], {"," identifier ":" typeExpr} ")" .
typeParameterList       ::=     "(" [identifier ":" "type"], {"," identifier ":"  "type"} ")" .
valfndefn               ::=     identifier ":" "valfn" adtType "="  scopedstmtlist .
```

```
namegendefn             ::=     identifier ":" "namegen" signature "->" signature "="  scopedstmtlist .
problemdefn             ::=     identifier ":" "probdef" signature "->" signature "=>" scopedPredStmtList .
predicatefndefn         ::=     identifier ":" "predicate" signature "@" signature "=>" scopedPredStmtList .
scopedstmtlist          ::=     "{" stmtlist "}" .
stmtlist                =       {stmt} .
stmt                    ::=     [ identornillist ((":" (condecl | typedecl | typeExpr)) | (assignop expr))
                                | "(" identornillist ")" assignop expr | matchstmt | iterstmt | sequencestmt
                                | foreachstmt | scopedstmtlist | operatorToleranceDecl] ";" .
operatorToleranceDecl   ::=     (hprecbinop | lprecbinop | unop) ":" typeExpr .
assignop                ::=     "=" | "^=" | "|=" | "&=" | "%=" | "/=" | "*=" | "-=" | "+=" | ">>="
                                | "<<=" | "<-=" | ":=" .
matchstmt               ::=     ("match" | "matchseq") "{" guardbody "}" .
iterstmt                ::=     "iter" "{" guardbody "}" .
sequencestmt            ::=     "sequence" "(" assignmentStatement ";" booleanExpression ";" assignmentStatement
                                ")" scopedStatementList .
foreachstmt             ::=     "foreach" "(" identifier "in" expr ")" scopedStatementList .
guardbody               =       {expr "=>" (stmtlist | scopedstmtlist)} .
expr                    ::=     (term {lprecbinop term}) | anonaggrcastexpr | chanevtexpr
                                | chan2nameexpr | var2nameexpr | name2chanexpr .
listcastexpr            =       "list" "of" initlist .
setcastexpr             =       "set" "of" initlist .
arrcastexpr             =       "array" (("of" idxinitlist) | ("[" integerConst "]" of starinitlist)) .
complexCastExpr         =       "complex" "(" arithConst "," arithConst ")" .
rationalCastExpr        =       "rat" expression expression .
anonaggrcastexpr        ::=     listcastexpr | setcastexpr | arrcastexpr | complexCastExpr | rationalCastExpr .
chanevtexpr             ::=     ("erasures" | "errors" | "latency") "of" identifier cmpop expr .
chan2nameexpr           ::=     "chan2name" factor [stringConst] .
var2nameexpr            ::=     "var2name" factor [stringConst] .
name2chanexpr           ::=     "name2chan" typeExpr expr realConst .
term                    ::=     [basictype] [unop] factor ["++" | "--"] {hprecbinop factor} .
factor                  ::=     (identifier {fieldselect}) | integerConst | realConst | stringConst | boolConst
                                | "(" expr ")" | tuplevalue | namegenInvokeShorthand | typeMinExpr | typeMaxExpr .
typeMinExpr             ::=     "typemin" "(" arithType ")" .
typeMaxExpr             ::=     "typemax" "(" arithType ")" .
namegenInvokeShorthand  ::=     identifier "(" [expr] {"," expr} ")" .
tuplevalue              ::=     "(" identornillist ")" .
fieldselect             ::=     ("." identifier) | ("[" expr [":" expr] "]") .
hprecbinop              ::=     "*" | "/" | "%" | "^" | "::" | "lowpass" | "highpass" | "dotproduct"
                                | "crossproduct" | "centralmoment" .
lprecbinop              ::=     "+" | "-" | ">>" | "<<" | "|"  | cmpop | booleanop .
cmpop                   ::=     "==" | "!=" | ">" | "<" | "<=" | ">=" .
booleanop               ::=     "&&" | "||" .
unop                    ::=     "~" | "!" | "-"  | "+" | "<-"  | "head" | "tail" | "len" | "sort" | "uncertainty"
                                | "tintegral" | "tderivative" | "timebase" | "sigfigs" | "samples" | "reverse"
                                | "fourier" | "typeof" | "cardinality" .
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} .
boolConst               ::=     "true" | "false" .
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" .
```

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Type Inference Rules for Operators

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$$\frac{M_1 : \tau \qquad M_2 : \texttt{list of } \tau}{M_1 \texttt{ :: } M_2 : \texttt{list of } \tau}$$

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

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

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).

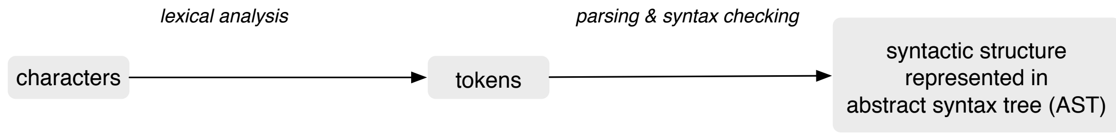


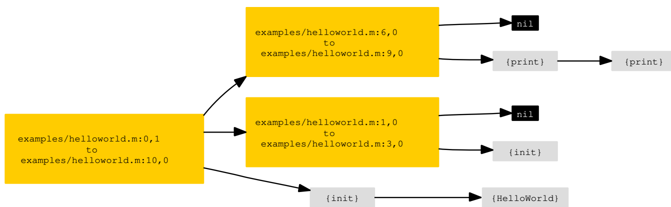
Fig. 20. Structure of the compiler.

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.

```
HelloWorld : progtype
{
        init    : namegen () -> ();
}

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

Fig. 22. An example program.



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

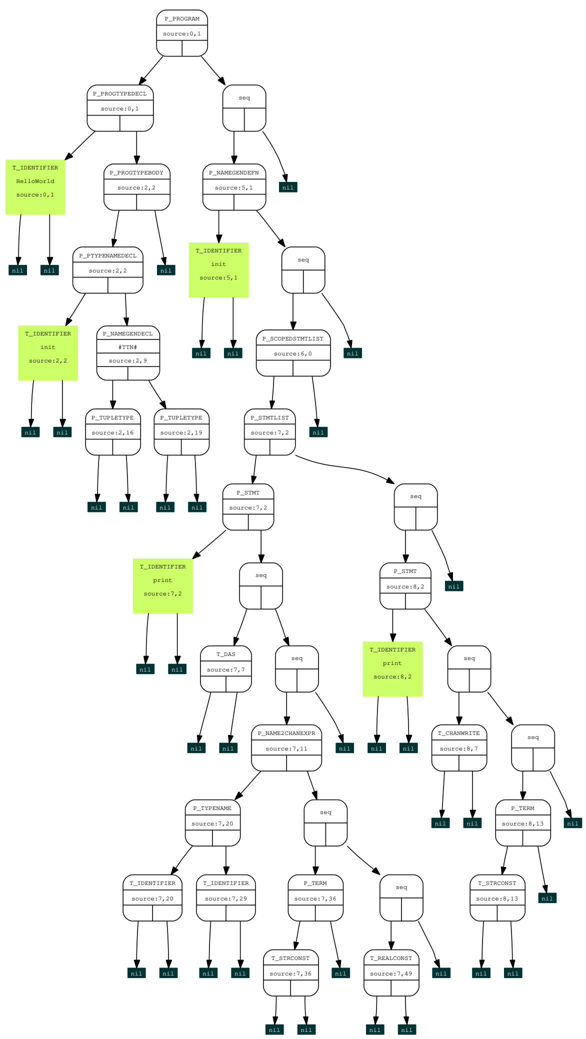


Fig. 23. Intermediate representation (Abstract Syntax Tree (AST)) of **HelloWorld** program. The Figure is generated automatically by the compiler.