Newton: A Language for Describing Physics

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Data from multiple sensors within an embedded computing system are often constrained in their relationship to each other. They are typically also constrained by general physical laws and by the structural design (e.g., size and aspect ratio) and materials properties (e.g., Young’s modulus) of the objects to which they are attached. Today, computing in embedded sensor platforms ignores this potentially rich source of information.

One way to exploit information about the physical context in which a given sensor-driven program will be deployed, is to modify the program (or its compiler) to implement algorithmic transformations that exploit information about inter- and intra-sensor relationships imposed by physical structure and materials properties. Alternatively, information about the physics of signals could be provided as a specification, in a machine-readable form, to be used by compilers and other analysis tools.

This article introduces Newton, a specification language for noting the analytic form, units of measure, and sensor signal properties for physical-object-specific invariants and general physical laws. We designed Newton to provide a means for hardware designers (e.g., sensor integrated circuit manufacturers, computing hardware architects, or mechanical engineers) to specify properties of the physical environments in which embedded computing systems will be deployed (e.g., a sensing platform deployed on a bridge versus worn by a human). Compilers and other program analysis tools for embedded systems can use a library interface to the Newton compiler to obtain information about the sensors, sensor signals, and inter-signal relationships imposed by the structure and materials properties of a given physical system. The information encoded within Newton specifications could enable new compile-time transformations that exploit information about the physical world.

Sensor data in physical systems are constrained by the laws of physics. Sensor data are also constrained by the mechanical design and materials properties of the objects in which sensors are embedded or to which they are attached. As a result, algorithms that process sensor data, such as the algorithms in pedimeters, unmanned aerial vehicles, autonomous land vehicles, robots, and more, consume input data that are constrained by physics. Compilers for embedded computing systems could exploit this observation to simplify arithmetic operations or to improve reliability in sensor signal processing.

Incorrect sensor readings affect systems built on top of those readings and can have catastrophic consequences: almost half of the accidents related to industrial chemical processes in one study were attributed to errors in temperature and pressure sensor readings. Similarly, erroneous pressure sensor readings have led directly to aviation accidents.

Information on physical constraints on a system’s sensor data could allow runtime assertions on the sensor data, analogous to probabilistic assertions. Information on physical constraints could also allow compile-time transformations that substitute code that reads from sensors of one type, with code that reads from sensors of a another type. Such sensor substitution is analogous to strength reduction in traditional compiler optimization and could have significant benefits to the energy efficiency and cost of sensor-driven systems.

To exploit these physical constraints that exist on sensor data, compilers of embedded programming languages require specifications of those constraints (Figure 1).

1. Newton

Newton is a language for specifying dimensionally-annotated constraints and invariants on values obtained from sensors embedded in physical structures. The Newton specification compiler provides a library interface that programming language compilers can use to obtain information about the physical constraints on the signals in the programs they process. Compiled programs and runtime systems can also access information about their physical environments and sensor invariants using Newton’s runtime library, which provides routines for runtime querying of invariant properties.

A. Example. The example below shows the Newton specification for the relationship between the period of an idealized simple pendulum, the distance between the pivot point of the pendulum and its primary mass, and constants (e.g., acceleration due to gravity).

```
time: signal = {  // constant
  name = "second" English;
  symbol = s;
  derivation = none;
}

length: signal = {  // constant
  name = "meter" English;
  symbol = m;
  derivation = none;
}

mass: signal = {  // constant
  name = "kilogram" English;
  symbol = kg;
  derivation = none;
}

Pi : constant = 3.14;
g : constant = 9.8; \text{m/s}^2;  // constant

pendulum: invariant(L: length, period: time) = {  // constant
  period = 2*Pi*sqrt(L/g) = \langle 1/2 \rangle
}
```

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2. Related Research

Dimensional analysis has been a valuable tool in science and engineering disciplines for over a century. Early work by Buckingham [7], laid the foundations for the more systematic study and application of dimensions in both design and system evaluation. Central to many modern applications of dimensional analysis has been the Buckingham Π theorem, which states that any constraint between \( n \) physical quantities, comprising \( k \) dimensionally-independent physical quantities, can be represented using a reduced number, \( n - k \), of monomial expressions constructed from the original \( n \) physical quantities.

In programming languages, introducing dimension types has been explored through both built-in types and libraries. House [8] proposed extending the Pascal language with units and dimensions, and F# [9] includes mechanisms for a programmer to declare dimensions of physical quantities. F# allows programmers to use these dimension types in programs, and provides support for type checking and type inference based on a dimension unification algorithm [10]. Similarly, XeLda [11] provides type checking for data in Excel spreadsheet programming.

Unlike techniques and systems for expressing and checking dimensions in programming languages, the objective of Newton is instead to allow sensor manufacturers, embedded system hardware platform manufacturers, industrial design engineers, and physicists to describe mechanical and other physical invariants obeyed by physical artifacts instrumented with sensors. Programming language compilers can then use these specifications to guide static compile-time and dynamic run-time program transformations. Newton enables compilers to extend their use of physical information beyond dimension type checking: Using information on sensor signal relationships obtained from Newton at compile time or at runtime, code generated by compilers that use Newton could check not only dimensions, but also physics-derived and platform-specific signal property invariants.

3. Newton Descriptions

There are three components of a Newton description: signal definitions, constant definitions, and invariant definitions.

A. Signals. Signals in Newton define either fundamental or derived signals, and their units. They typically represent signals that can be read from sensors on a hardware platform, such as acceleration from accelerometers, magnetic flux density from magnetometers, and angular rate from gyroscopes. Some fundamental signal types (e.g., time) exist primarily to be able to define derived signal types relevant to sensors, while others directly represent the signals of sensors (e.g., temperature). The Newton language does not specify which signals are fundamental a priori, and a Newton specification can define its own choice of fundamental signals. The compiler installation provides a standard set of signal definitions and in practice most Newton descriptions build on top of this standard set of definitions.

All signal definitions in Newton have a derivation statement. Fundamental signals have none as their derivation, while non-fundamental signals have a derivation which is a monomial expression comprising previously-defined fundamental or derived signals.

Newton specifications can define multi-dimensional signals, as the examples of the signals distance and speed below illustrate. Example uses of multi-dimensional signals include sensors such as 3-axis accelerometers and specifying signals from a single sensor sampled at different locations in space.

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The name field of a signal definition is a human-readable word or phrase describing the signal in a specific set of units and therefore includes a language designator (e.g., English). The symbol field in a signal definition specifies a token that can be used as an alias for a specific unit for the signal. For example, distance in the example above is defined as a fundamental signal (derivation = none) with units description "meter" and unit symbol m. This approach is similar to aliasing in F# [9].

B. Constants. Constants are fixed values with a dimension formed from a monomial expression of previously-defined signals. Constants can also be dimensionless, such as the mathematical constant \( \pi \):

\[
\begin{align*}
\text{speedLimit} & = \text{distance} / \text{time}; \\
\text{time} & : \text{signal} = \{ \\
& \text{name} = "\text{second}"; \\
& \text{symbol} = \"s\"; \\
& \text{derivation} = \text{none}; \\
\} \\
\text{distance} & : \text{signal} = \{ \\
& \text{name} = "\text{meter}"; \\
& \text{symbol} = \"m\"; \\
& \text{derivation} = \text{none}; \\
\} \\
\end{align*}
\]

\[
\begin{align*}
\text{speed} & : \text{signal} = \{ \\
& \text{name} = "\text{meters/sec}"; \\
& \text{symbol} = \"m/s\"; \\
& \text{derivation} = \text{distance} / \text{time}; \\
\} \\
\end{align*}
\]

The \( \pi \) field of a signal definition includes a human-readable word or phrase describing the signal in a specific set of units and therefore includes a language designator (e.g., English). The \( \pi \) field in a signal definition specifies a token that can be used as an alias for a specific unit for the signal. For example, distance in the example above is defined as a fundamental signal (derivation = none) with units description "meter" and unit symbol m. This approach is similar to aliasing in F# [9].

C. Invariants. Invariant definitions take in a list of parameters (signals and constants) with designated dimensions and define a physical relationship between those parameters and previously-defined signals and constants. The bodies of Newton invariants are comma-separated lists of expressions involving a relational operator and these expressions are interpreted as being in a conjunction.

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