Guiding user annotations for units-of-measure verification

DOMINIC ORCHARD, University of Kent
MISTRAL CONTRASTIN, Facebook London
MATTHEW DANISH, University of Cambridge
ANDREW RICE, University of Cambridge

This extended abstract reports on previous work of the CamFort project in which we developed an external units-of-measure type system for Fortran code, targeted at scientists. Our approach can guide the programmer in adding specifications (type annotations) to existing code, with the aim of easing adoption on legacy code. Pertinent to the topics of the HATRA workshop, we discuss the human-aspects of the tool here. CamFort is open-source and freely available online.

In modern science, it is common for models of the real world to be expressed as computer programs. Such programs are often highly numerical, dealing in quantities expressing real-world values. Most mainstream programming languages can only treat such values as uniformly typed (usually floats or doubles), yet the meaning of these values is often much richer: they have a dimension (e.g., time or length) and a unit-of-measure (e.g., seconds or metres), and perhaps even a kind of quantity [4] (e.g., angular momentum or linear momentum). Checking the consistency of units-of-measure or dimensionality in equations is a method long employed by scientists [8]. However, units checking has not been widely adopted in scientific programming despite the familiarity of the technique and a multitude of proposed systems for verification of units-of-measure [2, 5, 6, 11, 12, 15] (many influenced by the work of Kennedy [7] on expressing units-of-measure as a type system). One explanation for this lack of adoption is the burden of adding units annotations to existing codebases, which may be large [14]. For example, we previously observed a ratio of $\approx 1:10$ between variable declarations and lines of physical code in scientific Fortran code [9]. If each variable requires a units-of-measure specification then the burden of adopting such a system becomes prohibitively large for even medium-sized code bases (we found 10kloc programs had about 1k variables [9]). For code bases with over a million lines (e.g., the Met Office’s Unified Model for climate and weather forecasting [18]) writing $\approx 100,000$ specifications is even more of a non-starter.

However, given an adequate type inference procedure, it is almost certainly not necessary for a programmer to annotate every variable with its unit. For example, for $v = \frac{d}{t}$, we need only know the units of $d$ and $t$ to determine $v$ automatically. Indeed, in a study of a corpus of small Fortran programs, we found that unit-of-measure inference could reduce the annotation burden by about 80% [9]. Even with this reduction, how does a programmer faced with perhaps thousands of variables decide which ones need a type annotation? In the above example it takes a moment’s thought to realise that annotating just $v$ is not adequate to determine the units of $d$ and $t$. Thinking about such constraints over an entire program quickly becomes infeasible for a programmer.

Yet units-of-measure typing could be highly beneficial in science (and engineering) where the stakes of making an error are high (the famous example is the loss of the $327$ million Mars Climate Orbiter due to a mismatch of Imperial vs. metric units [16]). Our goal was to develop a tool addressing the human aspects of units-of-measure verification to overcome these barriers to entry.

---

1Presented at HATRA 2020 (Workshop on Human Aspects of Types and Reasoning Assistants) colocated with SPLASH 2020.
2http://camfort.github.io/

Authors’ addresses: Dominic Orchard, University of Kent, D.A.Orchard@kent.ac.uk; Mistral Contrastin, Facebook London; Matthew Danish, University of Cambridge, mrd45@cam.ac.uk; Andrew Rice, University of Cambridge, acr31@cam.ac.uk.
Guiding the user – suggesting which variables to annotate

CamFort is a suite of verification tools, one of which provides units-of-measure types to Fortran as *extrinsic* properties of values (in the sense of Reynolds [13]) expressed as comments and checked or inferred by the external tool. The approach allows annotations to be incrementally added to a code base [3], differing to F#’s units-of-measure typing which are not easily applied incrementally.

CamFort provides a ‘suggest’ feature to address the problem of how a user knows which variables to annotate to maximally exploit inference and reduce the annotation burden. This feature reports the *critical variables*: a minimal (possibly non-unique) subset of program variables for which knowing their units determines the units of the remaining variables not in the critical set. This set is computed by applying the usual constraint generation for inference/checking of the units types. Such constraints are expressed as a matrix, on which Gaussian elimination is applied to compute an overall solution can be identified from the resulting reduced row-echelon form of the matrix [9].

As a demonstration, consider the (slightly abridged) Fortran program in Figure 1. Running ‘camfort units-suggest’ on this code returns:

```
sample.f90: 2 variable declarations suggested to be given a specification:
sample.f90 (3:11) t
sample.f90 (2:11) x
```

The user can specify their units-of-measure via type annotation comments written above the variable declarations, e.g., adding `= unit(m) :: x` and `= unit(s) :: t` before lines 2 and 3 respectively. The user can then use the units-infer mode to see the inferred unit specifications for the rest of the code, or units-check to check the code against the specifications.

Synthesising types and inserting them into users’ source code

```
1 real :: a, b
2 real :: x = 20.0
3 real :: t = 3.0
4 a = sqr(x)
5 b = sqr(t)
6 ! contains
7 real function sqr(y)
8 real :: y
9 sqr = y * y
10 end function
```

```
1 ! contains
2 real function sqr(y)
3 real :: y
4 sqr = y * y
5 end function
```

The result for the Figure 1 program is shown in Figure 2. Note that the `sqr` function is unit-polymorphic and so is given a polymorphic specification, where ‘a’ means any unit (using ML-style syntax).

This specification synthesis technique is provided by other verification features of CamFort [1, 10]. We think this is an underused technique: compilers with type inference could potentially provide an analogous feature, aiding user understanding and documentation.

Lessons learned

We think there are two useful ideas here that can be applied elsewhere to improve human-computer interaction with verification tools: (1) use the constraints of checking or inference to guide the user to insert a minimal set of specifications which maximise information; (2) synthesise inferred specifications into source code. This may be best done ‘on request’, at specific locations given by the user, akin to how program synthesis tools can insert synthesised programs directly into code. A similar idea is seen in type qualifier inference tools such as Cascade [17], with guided annotation and specification generation.
REFERENCES

[1] Mistral Contrastin, Matthew Danish, Andrew C Rice, and Dominic A Orchard. 2016. Supporting software sustainability with lightweight specifications. In CEUR Workshop Proceedings, Vol. 1686.

[2] Mistral Contrastin, Andrew Rice, Matthew Danish, and Dominic Orchard. 2016. Units-of-measure correctness in Fortran programs. Computing in Science & Engineering 18, 1 (2016), 102–107.

[3] Matthew Danish, Dominic Orchard, and Andrew Rice. 2020. Incremental units-of-measure verification. Unpublished manuscript.

[4] Marcus P Foster. 2017. Quantity correctness in Fortran programs. Computing in Science & Engineering 19, 4 (2017), 83–87.

[5] Lingxiao Jiang and Zhendong Su. 2006. Osprey: A practical type system for validating dimensional unit correctness of C programs. In Proceedings of the 28th International Conference on Software Engineering. ACM, 262–271.

[6] Andrew Kennedy. 2009. Types for Units-of-Measure: Theory and Practice. Springer Berlin Heidelberg, Berlin, Heidelberg, 268–305. https://doi.org/10.1007/978-3-642-17685-2_8

[7] Andrew John Kennedy. 1996. Programming languages and dimensions. Technical Report. University of Cambridge, Computer Laboratory.

[8] Enzo O. Macagno. 1971. Historico-critical review of dimensional analysis. Journal of the Franklin Institute 292, 6 (1971), 391–402. https://doi.org/10.1016/0016-0032(71)90160-8

[9] Dominic Orchard, Andrew Rice, and Oleg Oshmyan. 2015. Evolving Fortran types with inferred units-of-measure. Journal of Computational Science 9, Supplement C (2015), 156 – 162. https://doi.org/10.1016/j.jocs.2015.04.018 Computational Science at the Gates of Nature.

[10] Dominic A. Orchard, Mistral Contrastin, Matthew Danish, and Andrew C. Rice. 2017. Verifying spatial properties of array computations. Proc. ACM Program. Lang. 1, OOPSLA (2017), 75:1–75:30. https://doi.org/10.1145/3133899

[11] John-Paul Ore, Carrick Detweiler, and Sebastian Elbaum. 2017. Lightweight Detection of Physical Unit Inconsistencies Without Program Annotations. In Proceedings of the 26th ACM SIGSOFT International Symposium on Software Testing and Analysis (ISSTA 2017). ACM, New York, NY, USA, 341–351. https://doi.org/10.1145/3092703.3092722

[12] Gerke Max Preussner. 2018. Dimensional Analysis in Programming Languages. https://gmpreussner.com/research/dimensional-analysis-in-programming-languages. Accessed: 2020-11-11.

[13] John C Reynolds. 2000. The meaning of types from intrinsic to extrinsic semantics. BRICS Report Series 7, 32 (2000).

[14] Omar-Alfred Salah. 2019. Understanding Reasons Behind the Lack of Adoption of Units of Measure (UoM) Libraries.

[15] WV Snyder. 2013. ISO/IEC JTC1/SC22/WG5 N1969: Units of measure for numerical quantities. Technical Report. International Organization for Standardization. http://wg5-fortran.org/N1951-N2000/N1969.pdf

[16] Arthur G Stephenson, Daniel R Mulville, Frank H Bauer, Greg A Dukeman, Peter Norvig, Lia S LaPiana, Peter J Rutledge, David Foltz, and Robert Sackheim. 1999. Mars Climate Orbiter Mishap Investigation Board Phase I Report. Technical Report. NASA.

[17] Mohsen Vakilian, Aamar Phaosawasdi, Michael D Ernst, and Ralph E Johnson. 2015. Cascade: A universal programmer-assisted type qualifier inference tool. In 2015 IEEE/ACM 37th IEEE International Conference on Software Engineering, Vol. 1. IEEE, 234–245.

[18] Damian R Wilson and Susan P Ballard. 1999. A microphysically based precipitation scheme for the UK Meteorological Office Unified Model. Quarterly Journal of the Royal Meteorological Society 125, 557 (1999), 1607–1636.