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## Abstract

The current state of Scientific Computing software development leaves room for improvement. There is a need for improved software quality, more consistent use of software engineering practices, and reduced information duplication. As it stands, information duplication creates a number of problems. Traceability is hard to achieve as finding the source of a piece of information is difficult among the possibilities. Over time this impacts the maintainability of a piece of software, as developers may not be able to track down the source of a problem. Also, with many duplicated information sources, it makes creating documentation more difficult, reducing a developer's desire to produce and maintain high-quality documentation. I want to facilitate the improvement of qualities (maintainability, traceability, reproducibility, etc.) across all artifacts of a piece of software. I believe a knowledge-based approach, which borrows ideas from literate programming, and involves a larger short-term investment from developers is the first step to improving software as a whole. I am creating a framework (Drasil) to facilitate this approach, focusing on avoiding knowledge duplication, while improving traceability and automating as much of the development process as possible. I believe with the proper tools for automation we can ensure good software engineering practices are followed (regardless of the developer's background) and improve the overall quality of software.

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# 1 Introduction

I want everyone to make better software. I believe this can be achieved by improving software qualities such as maintainability, traceability, verifiability, reproducibility, and reusability. As that is too broad of a target, I will be focusing on well-understood domains; specifically Scientific Computing (SC). SC has a very rich, well-understood background, but tends to suffer from a lack of high-quality software and tools. In many cases, SC developers are scientists first and lack a strong software engineering background.

Scientists and engineers also heavily rely on models that share common mathematical/scientific knowledge. Common sense would dictate that these models should be created once and reused as necessary, across any applicable projects. However, that is often not the case as many models are reimplemented for each new project. Therefore, I intend to address this problem and hope to improve the reuse of knowledge for scientific models.

Multiple implementations of the same model is not my only concern involving duplication. A typical software project involves many different software artifacts (requirements and design documents, test cases, source code, manuals, etc.), each of which contain (some subset of) the same underlying scientific knowledge. Essentially, this knowledge is duplicated as necessary into each of the requisite artifacts for a project. As the project evolves, some of this knowledge will inevitably change, leading to issues with inter-artifact consistency until someone manually updates each artifact after the change is made. With small changes, these updates can be done fairly quickly (though it may be tedious), but for larger changes the update process for each artifact is far more resource intensive. Oftentimes, these changes are not recorded across all artifacts due to a lack of resources.

As artifacts in a software project begin to fall out of sync with each other, the qualities of the project as a whole suffer. This usually happens because these qualities (traceability, maintainability, verifiability, reproducibility, etc.) are hard to quantify and not seen as being as critical as traits such as correctness, accuracy, or performance. When artifacts become inconsistent, traceability can be lost completely and maintenance becomes much more difficult.

I think the first step to improving software as a whole is to improve each of the software artifacts. To that end, I would like to expand the ideas of literate programming (which I will discuss more in-depth in Section 2.2). Specifically, I want to keep the idea of *chunks* and expand its application to not only code snippets, but the fundamental knowledge underlying a piece of software.

I am not creating any individual new ideas. Instead, I want to combine ideas that have existed for some time and use them in a novel way. That is where the idea of a knowledge-based approach to literate software comes from. Not only do I want to create better software using a process similar to literate programming, but I want to ensure that process will cover all necessary software artifacts.

To that end, I believe a tool will be necessary to facilitate my approach. A framework known as “Drasil” is currently in development and will be explained

in Section 4.

## 2 State of the Art

To pursue this line of research, first one needs to understand the history of research in several closely-related areas. Since I will be focusing on the improvement of SC software, the obvious starting point would be to look at the current state of SC software development and its challenges. Also, as I am intending to expand the ideas of literate programming, it is necessary to delve into sufficient depth on LP and why it has not been widely adapted as yet, as well as any attempts to expand or build upon it. Finally, with the idea of long-term maintainability, full traceability, and reproducibility in mind, I would be remiss if I did not look into the field of reproducible research.

### 2.1 Current State of SC Software Development

In many instances of SC software development, the developers are the scientists. These developers tend to put the most emphasis on their science instead of good software development practices [13]. Rigid, process-heavy approaches are typically considered unfavourable to these developers [4]. We see the developers choose to use an agile philosophy [1, 4, 6, 28], an amethodical [11], or a knowledge acquisition driven process [12] instead.

There are several clear problems with the current state of SC software development. The first, fairly obvious problem is that knowledge reuse is not being utilized to the fullest extent possible. As an example, a survey [21] showed that of 81 different mesh generator packages, 52 generated triangular meshes. Now that in itself may not show a lack of knowledge reuse, however, looking deeper we see that 37 of those packages used the same Delaunay triangulation algorithm for generating those meshes. There is no reason that the exact same algorithm should be implemented 37 separate times when it could simply be reused.

Another problem in SC software development is the lack of understanding of software testing. More than half the scientists developing SC software lack a good understanding of software testing [18]. It is in such a bad state that quality assurance has “a bad name among creative scientists and engineers” [26, p. 352], not to mention the very limited use of automated testing [22].

It should be obvious that some of these issues could be solved through the use of certain tools. However, it should be noted that tool use by SC software developers is also very limited, especially the use of version control software [36].

Not everything about SC software development today is a negative. For example advanced techniques like code generation have been quite successful in SC. Some generation examples that come to mind are FEniCS [17], FFT [14], Gaussian Elimination [3], and Spiral. The focus of generation techniques, thus far, have been solely on one software artifact: the source code. Focusing solely on code is a disadvantage to SC software developers as the value of documentation,

as well as a structured (or rational) process, have been repeatedly illustrated [31, 32, 33, 34].

## 2.2 Literate Programming

The LP methodology introduced by Knuth changes the focus from writing programs that simply instruct the computer on how to perform a task to explaining (*to humans*) what we want the computer to do [15].

Developing literate programs involves breaking algorithms down into *chunks* [10] or *sections* [15] which are small and easily understandable. The chunks are ordered to promote understanding, a “psychological order” [24] if you will. They do not have to be written in the same order that a computer would read them. It should also be noted that in a literate program, the code and documentation are kept together in one source. To extract working source code, a process known as *tangle* must be run on the source. A similar process known as *weave* is used to extract and typeset the documentation from the source.

There are many advantages to LP beyond understandability. As a program is developed and updated, the documentation surrounding the source code tends to be updated simultaneously. It has been experimentally found that using LP ends up with more consistent documentation and code [29]. Having consistent documentation has its own advantages while developing or maintaining software [9, 16]. Similarly, there are many downsides to inconsistent documentation [16, 35]. Keeping both of those in mind we can see that more effective, maintainable code can be produced when (properly) using LP [24].

Even with all of the benefits of LP, it has not been very popular [29]. Though it has not been popular, there are still several successful examples of LP’s use in SC; two that come to mind are VNODE-LP [20] and “Physically Based Rendering: From Theory to Implementation” [23]. The latter being a literate program as well as a textbook. Shum and Cook discuss the topic of LP’s lack of popularity and present the idea that it comes from a couple of main issues: dependency on a particular output language or text processor, the lack of flexibility on what should be presented/suppressed in the output.

Many attempts to address the issues with LP’s popularity have focused on changing or removing the output language or text processor dependency. Many new tools were developed such as: CWeb (for the C language), javadoc (for Java), DOC++ (for C++), Doxygen (for multiple languages), noweb (programming language independent), and more. The development of new tools led the introduction of many new features including, but not limited to, a “What You See Is What You Get” (WYSIWYG) editor [7], phantom abstracting [29], and even movement away from the “one source” idea [30].

While these tools did not bring LP into the mainstream [25], they did help drive the understanding behind what exactly LP tools must do. Although LP is not yet mainstream, we can see it becoming more standardized in certain domains (for example: Agda, Haskell, and R support LP).

## 2.3 Literate Software

A combination of LP and Box Structure [19] was proposed as a new methodology called “Literate Software Development” (LSD) [2]. Box structure can be summarized as the idea of different views (ex. system specifications, design, code) which are abstractions that communicate the same information in different levels of detail, for different purposes.

LSD was developed with the intent to overcome the disadvantages of both LP and box structure. It was intended to overcome LP’s inability to specify interfaces between modules, the inability to decompose boxes and implement the design created by box structures, as well as the lack of tools to support box structure [5].

The framework developed for LSD, “WebBox”, expanded LP and box structures in a variety of ways. It included new chunk types, the ability to refine chunks, the ability to specify interfaces and communication between boxes, and the ability to decompose boxes at any level. However, literate software (and LSD) remain primarily code-focused with very little support for creating other software artifacts.

## 2.4 Reproducible Research

Being able to reproduce results is fundamental to the idea of good science. Reproducible research has been used to mean embedding executable code in research papers to allow readers to reproduce the results described [27].

Combining research reports with relevant code, data, etc. is not necessarily easy, especially when dealing with the publication versions of an author’s work. As such, the idea of *compendia* were introduced [8] to provide a means of encapsulating the full scope of the work. Compendia allow readers to see computational details, as well as re-run computations performed by the author. Gentleman and Lang proposed that compendia should be used for peer review and distribution of scientific work [8].

Currently, several tools have been developed for reproducible research including, but not limited to, Sweave, SASweave, Statweave, Scribble, and Org-mode. The most popular of those being Sweave [27]. The aforementioned tools maintain a focus on code and certain computational details. It is my hope that the Drasil framework will one day surpass these tools due to its ability to simplify the creation of all software artifacts.

# 3 Research Objectives and Approach

## 3.1 Objectives

Looking at the current state of SC software development, there are many areas for improvement particularly the need for applying better software engineering practices and improving knowledge reuse. The simplest approach for improving development would be to get better developers, which is not necessarily feasible

for SC software. Software engineering education is not typically part of an SC developer’s background, and having software engineers develop SC software is problematic because the software engineers typically lack the necessary domain knowledge. Domain experts require tools that simplify the software engineering process so they can do things the “right” way. My first objective, therefore, is to simplify the software development process by allowing scientists to focus on the science.

My second objective is to increase software qualities (maintainability, traceability, reproducibility, verifiability, reusability, etc.) in SC software. The first step toward this improvement is to better understand the fundamental scientific background underlying said software. As such I will be focusing on understanding and capturing that knowledge.

My third objective, a natural progression from the second, is better overall software artifacts (requirements and design documents, source code, etc.). It is a worrying trend that software artifacts tend to fall out of sync with each other over time, so ensuring they remain consistent is a means to improve.

Furthermore, developers should not need to spend large swaths of time updating and maintaining their software. I would like to automate as much of the software development process as possible. Automation will also allow developers to avoid some classical software mistakes such as duplication, previously mentioned in the survey by Owen [21]. It will also ensure reproducibility as, if done right, anyone will be able to automatically create and run the same software easily.

## 3.2 Approach

To meet my objectives I am using a combination of existing ideas, which I have dubbed a *knowledge-based* approach to software development. First off, I want to expand and use ideas from LP. Namely, the brilliant idea of chunks, however, it should be expanded to represent encapsulated knowledge. If the knowledge behind an underlying concept can be properly encapsulated, then it can easily be reused and duplication can be avoided.

Knowledge encapsulation should be done at the specification level instead of the code level. It will include assumptions, derivations, equations, etc. and from there it is a fairly simple and straightforward process to get a code representation. Specifically, the high-level knowledge can be used for the automatic generation of code.

The standard LP style helps to increase consistency in documentation, but it does not go far enough. It is easy for a developer to update the code and/or documentation, however, there is no way to ensure that when the code is changed the documentation is also updated accordingly. I want to ensure that all artifacts are updated any time there is a change (no matter how trivial) with trivial effort.

This automatic updating is achieved through generation. The idea is to have a standard generator which uses *recipes* for the creation of artifacts. Each recipe essentially defines a different view of our knowledge-base (chunks). Since each recipe represents a different software artifact and pulls appropriate knowledge



from reusable chunks, the artifacts will remain consistent and fully traceable; finding the source of a piece of information will be trivial. All artifacts will be updated automatically any time the generator is run, thus ensuring consistency is maintained. Also, giving anyone access to the recipes and chunks used will allow them to reproduce a piece of software.

I am currently taking a practical, example-driven approach to create a framework (called *Drasil*) to exemplify this knowledge-based approach to software development. Thus far, the implementation of Drasil has been guided by some small and fairly specific case studies. However, I plan to continue expanding the framework through the use of larger, more varied case studies. More information regarding Drasil can be found in the next section.

## 4 Current Work and Preliminary Results

### 4.1 The Drasil Framework

Drasil is currently being implemented as a combination of embedded Domain Specific Languages (eDSLs) in Haskell. I have currently implemented six eDSLs as follows:

1. Expression language – A simple expression language that allows us to capture knowledge relating to equations and mathematical operations. It includes operations such as addition, multiplication, derivation, and exponentiation among others.
2. Expression layout language – A micro-scoped language for describing how expressions should appear. Expressions may need to use a variety of inline layout modifiers (subscripts, superscripts, etc.) to be properly displayed.
3. Document layout language – A macro-scoped language for describing how large-scale layout objects (tables, sections, figures, etc.) should appear.
4. C Representation Language – A DSL for representing parts of the C programming language inside the Drasil framework. This allows the generator to produce working C code.
5.  $\text{\LaTeX}$  Representation Language – A DSL for representing  $\text{\LaTeX}$  code inside of Drasil. As with the C representation, it is used by the generator to produce working  $\text{\LaTeX}$  code.
6. HTML Representation Language – A DSL for representing HTML within Drasil. Similar to the other representation languages as it is used by the generator to produce working HTML.

With these eDSLs it is easy to encapsulate knowledge, create recipes, and generate required artifacts.

When it comes to chunks, they come in several varieties. You can see a hierarchy of chunk types in Figure 1.

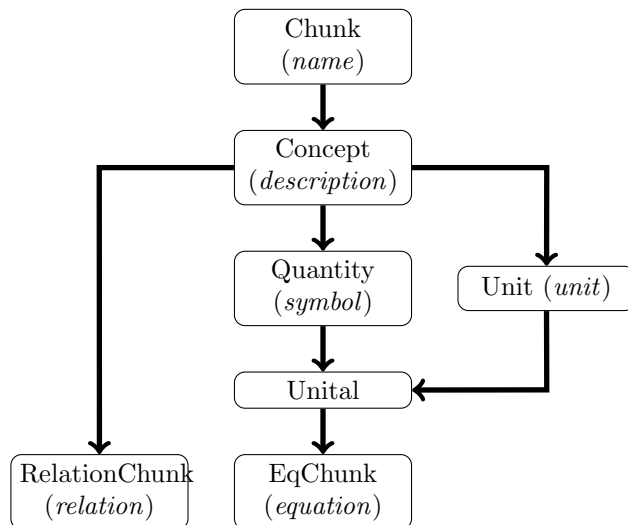


Figure 1: Our current chunk design (parentheses indicate newly added knowledge)

Each new chunk in the hierarchy adds to the knowledge encapsulated within it. The most basic *Chunk* represents a named piece of information. A *Concept* adds a description to the named information, and so on.

*Unital* chunks are somewhat special as they do not add any new information in and of themselves, they act as a combination of a *Quantity* (concept with a symbolic representation) and a *Unit*. They are quantities with units.

*Equation* chunks continue to expand on *Unital* chunks by allowing us to capture equations for calculating quantities. In a similar vein are *Relation* chunks, which allow us to relate two pieces of knowledge to each other.

Now that knowledge has been encapsulated it is time to do something with it. This is where the recipes, mentioned earlier, come into play. Writing a recipe requires using three of the previously mentioned eDSLs – the expression, expression layout, and document layout languages. I will go into more detail on writing and using recipes in the next section.

Finally, the last piece of the implementation is the generator. The remaining three representation languages are specific to the generator. The generator interprets the recipes and creates intermediary representations of artifacts using the representation languages, then pretty-prints the results.

## 4.2 Using Drasil

For this section I will touch on two case studies that I have used to motivate the development of Drasil. The first is a simplified version of a Software Requirements Specification (SRS) for a fuel pin in a nuclear reactor [31] and the

Number	DD2
Label	$h_c$
Units	$ML^0t^{-3}T^{-1}$
SI Units	$\frac{kW}{m^2\circ C}$
Equation	$h_c = \frac{2k_c h_b}{2k_c + \tau_c h_b}$
Description	$h_c$ is the convective heat transfer coefficient between clad and coolant $k_c$ is the clad conductivity $h_b$ is the initial coolant film conductance $\tau_c$ is the clad thickness

Figure 2: Data definition for  $h_c$  from the fuel pin SRS

```

h_c_eq :: Expr
h_c_eq = 2*(C k_c)*(C h_b) /
  (2*(C k_c) + (C tau_c)*(C h_b))

h_c :: EqChunk
h_c = fromEqn "h_c"
  "convective heat transfer coefficient
   between clad and coolant"
  (sub h c) heat_transfer h_c_eq

```

Figure 3: The  $h_c$  chunk in Drasil

second is a SRS for a solar water heating tank.

Let's start by looking at a single term from the fuel pin SRS:  $h_c$ . This term represents the convective heat transfer coefficient between the clad and coolant. We can see the data definition for this term in Figure 2.

From the data definition, we can glean interesting knowledge. First off there is the name of the concept, its description, the symbol representing it, its SI units, and its defining equation. All of this information can be encapsulated into an EqChunk with ease as shown in Figure 3. Note that the units for  $h_c$  are defined in a piece of common knowledge known as **heat\_transfer**.

The SI Units are a great example of common knowledge. The SI Unit library contains all seven base SI units and several different derived units (for example degrees Celsius, which are derived from Kelvin). The seven fundamental base SI units implemented in Drasil can be seen in Figure 4.

From the captured knowledge and common knowledge, it is now possible to start putting together a document using recipes. A small portion of the recipe for the simplified fuel pin SRS can be seen in Figure 5. Currently the recipes

metre, second, kelvin, mole, kilogram, ampere, candela	:: FundUnit
metre = fund "Metre"	"length (metre)" "m"
second = fund "Second"	"time (second)" "s"
kelvin = fund "Kelvin"	"temperature (kelvin)" "K"
mole = fund "Mole"	"amount of substance (mole)" "mol"
kilogram = fund "Kilogram"	"mass (kilogram)" "kg"
ampere = fund "Ampere"	"electric current (ampere)" "A"
candela = fund "Candela"	"luminous intensity (candela)" "cd"

Figure 4: The seven fundamental SI Units in Drasil

```
srsBody = srs [h-g, h-c] "Spencer Smith" [s1,s2,s3]

s1 = Section (S "Table of Units") [intro, table]

table = Table
  [S "Symbol", S "Description"] (mkTable
    [(\x -> Sy (x ^. unit)),
     (\x -> S (x ^. descr)) ] si-units)

intro = Paragraph (S "Throughout this ...")
```

Figure 5: A portion of our simplified SRS recipe

are fairly clunky and rely heavily on Haskell, but in the future this will be improved. However, even with the current recipes we can see that the output from the generator (Figure 6) is exactly what we want. Note: the output I am showing is from the HTML version being generated, the TeX version looks (almost) identical to the original SRS.

Already several advantages of using Drasil and a knowledge based approach are obvious. First off, there are no inconsistencies in the knowledge both within and across artifacts. Manually copying knowledge is no longer necessary, and we can easily trace where a piece of knowledge came from. Should anything need updating, the updates will automatically propagate throughout the artifacts when the generator is run. We also have completely reusable knowledge (for example: the SI Units) and the use of recipes supports design for change. As long as knowledge is captured properly, it is as simple as changing a configuration file to change the software.

One advantage that may seem like a disadvantage (but is not) is that of pervasive bugs. Thanks to the full traceability and reuse of knowledge, a single bug will be reproduced anywhere that piece of knowledge is necessary. This improves the odds of finding it and makes it simple to fix. A single change should update all of the artifacts and remove the bug.

There are a few disadvantages to using the knowledge based approach with Drasil. The most obvious is the inability to include local hacks. Any human-modified generated file will lose its modifications the next time the generator is run.

## Table of Units

Throughout this document SI (Système International d'Unités) is employed as the unit system. In addition to the basic units, several derived units are employed as described below. For each unit, the symbol is given followed by a description of the unit with the SI name in parentheses.

Symbol	Description
m	length (metre)
kg	mass (kilogram)
s	time (second)
K	temperature (kelvin)
mol	amount of substance (mole)
A	electric current (ampere)
cd	luminous intensity (candela)
°C	temperature (centigrade)
J	energy (joule)
W	power (watt)
cal	energy (calorie)
kW	power (kilowatt)

Figure 6: Section 1 of the generated SRS (HTML version)

Finally, creating common-knowledge libraries is fairly difficult as it requires a domain expert to be involved.

## 5 Work Plan and Next Steps

A full schedule of my work plan can be found in Table 1. There are still many features I would like to add to Drasil as well as improvements to the overall implementation. Currently anticipated additions and changes (in no particular order) are as follows:

- Encapsulate more types of information in chunks. Some of the next additions should be physical constraints and reasonable values.
- Use constraints to generate test cases.
- Implement much larger examples.
- Generate code in more languages. Specifically MATLAB is the next planned output language implementation.
- Generate more artifact types. As it stands, the current recipes only create requirements documents or code. New recipes should be included to cover design documents, test cases, build instructions, user manuals, and more.

- Generate different document views. This is partially implemented in the requirements document recipe by allowing simplified or verbose data descriptions. The ability to simplify parts of the document that are unnecessary for a target audience should be expanded.
- Create an external syntax for Drasil.

Over the summer (2016), three undergraduate students will be working on translating existing implementations of large examples into Drasil implementations. It is my hope that this experiment will provide insight on any lacking features of Drasil, as well as how well the new approach works. A second PhD student will also be joining the project over the summer. His first task will involve implementing a large example and helping to expand Drasil.

Table 1: A detailed work schedule for the next twenty-eight months

Summer 2016	<p>Summer student experiment. Implement multiple (3-4) large examples using Drasil, updating the framework as new needs for features arise.</p> <p>Write up results of experiment as a paper and submit to SEH-PCCSE'16.</p>
Fall 2016	<p>Overhaul the Drasil back-end to solidify necessary features and redesign parts of the implementation.</p> <p>Finish PhD course requirements.</p> <p>Meet with Ernie from OPG.</p>
Winter 2016	<p>Implement external syntax for Drasil.</p> <p>Write a paper for ICSR (International Conference on Software Reuse).</p> <p>Write a journal paper for Automated Software Engineering.</p>
Spring 2017	<p>Re-evaluate current Drasil implementation for usability. Work on making it as user-friendly as possible.</p> <p>Submit a paper to Onward!</p> <p>Submit a paper to ASE (International Conference on Automated Software Engineering)</p> <p>Meet with committee.</p>
Summer 2017	<p>Write a paper.</p> <p>Attempt to get summer students for second round of experimentation.</p> <p>Write a journal paper detailing results.</p>
Fall 2017	<p>Meet with Ernie from OPG.</p> <p>Update Drasil and perform a final evaluation.</p>
Winter 2017	Begin writing up full PhD Thesis.
Spring 2018	<p>Complete first draft of thesis and send to supervisors for comments.</p> <p>Complete first round of edits.</p>
Summer 2018	Complete final thesis draft before defense. Make any necessary revisions to the thesis and submit it.

## References

- [1] Karen S. Ackroyd, Steve H. Kinder, Geoff R. Mant, Mike C. Miller, Christine A. Ramsdale, and Paul C. Stephenson. Scientific software development at a research facility. *IEEE Software*, 25(4):44–51, July/August 2008.
- [2] Shereef Abu Al-Maati and Abdul Aziz Boujarwah. Literate software development. *Journal of Computing Sciences in Colleges*, 18(2):278–289, 2002.
- [3] Jacques Carette. Gaussian elimination: a case study in efficient genericity with metaocaml. *Science of Computer Programming*, 62(1):3–24, 2006.
- [4] Jeffrey C. Carver, Richard P. Kendall, Susan E. Squires, and Douglass E. Post. Software development environments for scientific and engineering software: A series of case studies. In *ICSE '07: Proceedings of the 29th international conference on Software Engineering*, pages 550–559, Washington, DC, USA, 2007. IEEE Computer Society.
- [5] Michael Deck. Cleanroom and object-oriented software engineering: A unique synergy. In *Proceedings of the Eighth Annual Software Technology Conference, Salt Lake City, USA*, 1996.
- [6] Steve M. Easterbrook and Timothy C. Johns. Engineering the software for understanding climate change. *Computing in Science & Engineering*, 11(6):65–74, November/December 2009.
- [7] Peter Fritzson, Johan Gunnarsson, and Mats Jirstrand. Mathmodelica—an extensible modeling and simulation environment with integrated graphics and literate programming. In *2nd International Modelica Conference, March 18-19, Munich, Germany*, 2002.
- [8] Robert Gentleman and Duncan Temple Lang. Statistical analyses and reproducible research. *Journal of Computational and Graphical Statistics*, 2012.
- [9] Marco S Hyman. Literate c++. *COMP. LANG.*, 7(7):67–82, 1990.
- [10] Andrew Johnson and Brad Johnson. Literate programming using `noweb`. *Linux Journal*, 42:64–69, October 1997.
- [11] Diane Kelly. Industrial scientific software: A set of interviews on software development. In *Proceedings of the 2013 Conference of the Center for Advanced Studies on Collaborative Research, CASCON '13*, pages 299–310, Riverton, NJ, USA, 2013. IBM Corp.
- [12] Diane Kelly. Scientific software development viewed as knowledge acquisition: Towards understanding the development of risk-averse scientific software. *Journal of Systems and Software*, 109:50–61, 2015.
- [13] Diane F. Kelly. A software chasm: Software engineering and scientific computing. *IEEE Softw.*, 24(6):120–119, 2007.



- [14] Oleg Kiselyov, Kedar N Swadi, and Walid Taha. A methodology for generating verified combinatorial circuits. In *Proceedings of the 4th ACM international conference on Embedded software*, pages 249–258. ACM, 2004.
- [15] D. E. Knuth. Literate programming. *The Computer Journal*, 27(2):97–111, 1984.
- [16] Jeffrey Kotula. Source code documentation: an engineering deliverable. In *tools*, page 505. IEEE, 2000.
- [17] Anders Logg, Kent-Andre Mardal, and Garth Wells. *Automated solution of differential equations by the finite element method: The FEniCS book*, volume 84. Springer Science & Business Media, 2012.
- [18] Zeeya Merali. Computational science: ...error. *Nature*, 467:775–777, 2010.
- [19] Harlan D Mills, Richard C Linger, and Alan R Hevner. Principles of information systems analysis and design. 1986.
- [20] Nedialko S. Nedialkov. VNODE-LP — a validated solver for initial value problems in ordinary differential equations. Technical Report CAS-06-06-NN, Department of Computing and Software, McMaster University, 1280 Main Street West, Hamilton, Ontario, L8S 4K1, 2006.
- [21] Steven J. Owen. A survey of unstructured mesh generation technology. In *INTERNATIONAL MESHING ROUNDTABLE*, pages 239–267, 1998.
- [22] Matthew Patrick, James Elderfield, Richard OJH Stutt, Andrew Rice, and Christopher A Gilligan. Software testing in a scientific research group. 2015.
- [23] Matt Pharr and Greg Humphreys. *Physically Based Rendering: From Theory to Implementation*. Morgan Kaufmann Publishers Inc., San Francisco, CA, USA, 2004.
- [24] Vreda Pieterse, Derrick G. Kourie, and Andrew Boake. A case for contemporary literate programming. In *Proceedings of the 2004 Annual Research Conference of the South African Institute of Computer Scientists and Information Technologists on IT Research in Developing Countries*, SAICSIT '04, pages 2–9, Republic of South Africa, 2004. South African Institute for Computer Scientists and Information Technologists.
- [25] Norman Ramsey. Literate programming simplified. *IEEE software*, 11(5):97, 1994.
- [26] Patrick J. Roache. *Verification and Validation in Computational Science and Engineering*. Hermosa Publishers, Albuquerque, New Mexico, 1998.
- [27] Eric Schulte, Dan Davison, Thomas Dye, Carsten Dominik, et al. A multi-language computing environment for literate programming and reproducible research. *Journal of Statistical Software*, 46(3):1–24, 2012.

- [28] Judith Segal. When software engineers met research scientists: A case study. *Empirical Software Engineering*, 10(4):517–536, October 2005.
- [29] Stephen Shum and Curtis Cook. Aops: an abstraction-oriented programming system for literate programming. *Software Engineering Journal*, 8(3):113–120, 1993.
- [30] Volker Simonis. Progdok—a program documentation system. *Lecture Notes in Computer Science*, 2890:9–12, 2001.
- [31] Spencer Smith and Nirmitha Koothoor. A document driven method for certifying scientific computing software used in nuclear safety analysis. *Nuclear Engineering and Technology*, Accepted, 2016. 42 pp.
- [32] Spencer Smith, Yue Sun, and Jacques Carette. Comparing psychometrics software development between CRAN and other communities. Technical Report CAS-15-01-SS, McMaster University, January 2015. 43 pp.
- [33] Spencer Smith, Yue Sun, and Jacques Carette. Statistical software for psychology: Comparing development practices between CRAN and other communities. *Software Quality Journal*, Submitted December 2015. 33 pp.
- [34] W. Spencer Smith, Nirmitha Koothoor, and Nedialko Nedialkov. Document driven certification of computational science and engineering software. In *Proceedings of the First International Workshop on Software Engineering for High Performance Computing in Computational Science and Engineering (SE-HPCCCE)*, page [8 p.], November 2013.
- [35] Harold Thimbleby. Experiences of ‘literate programming’ using cweb (a variant of knuth’s web). *The Computer Journal*, 29(3):201–211, 1986.
- [36] Gregory V. Wilson. Where’s the real bottleneck in scientific computing? Scientists would do well to pick some tools widely used in the software industry. *American Scientist*, 94(1), 2006.