Writing-to-Learn-to-Program: Examining the Need for a New Genre in Programming Pedagogy

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We are a nation driven by code, dependent on programs for our everyday lives. Vital aspects of our national security depend on our ability to withstand daily cyber intrusions into Department of Defense assets; likewise, our economic security rests on the ability of banks and stock exchanges to securely move millions of dollars electronically. Our nation’s infrastructure depends on the smart grid and thousands of other process control systems that manage our water supplies, run our factories, and operate our cars. The social lives of millions of Americans rely on social networking, smart phones and tablets, and a high-speed internet backbone. Serious, sometimes fatal bugs such as Toyota’s $1.2 billion dollar penalty\(^1\) for unintended acceleration\(^2\), Shellshock\(^3,4\), and Heartbleed\(^5\) all demonstrate the need for proficient programmers.

Despite the constantly increasing need for qualified engineers with strong programming abilities, the difficulty of teaching introductory programming still stands as a barrier to many STEM disciplines. A multi-institutional, multi-national experiment conducted by the McCracken group\(^6\) reported only a little over 20% of students were able to solve the types of programming problems expected by their instructors. It is essential to properly prepare the people who power our security, our economy, and our lives.

In this paper, we present a new genre in computer science education that is aimed at improving student learning and application of programming concepts. Based on the well-acknowledged effectiveness of the writing across the curriculum (WAC) and Writing-to-Learn (WTL) movements, this paper employs the intermingling of writing activities with coding, which has the potential to dramatically impact the programming learning process. We term this approach Writing-to-Learn-to-Program (WTLTP). Following our discussion of the WTLTP genre, we present technologies that support the genre and discuss our future efforts to investigate the effectiveness of WTLTP in the classroom environment. This paper contributes both to WTL literature by incorporating WTL principles into a new domain and to computer science education literature by proposing a new approach to introductory computer science courses (CS1).

1. From writing-to-learn (WTL) to writing-to-learn-to-program (WTLTP)

WTL strategies arose from the writing across the curriculum (WAC) movement, which can be traced back to the 19th century in the U.S. It describes programs that emphasize the connection between writing and learning, but the term also refers to the pedagogical theories that support this connection. In the following sections, the history and influence of WTL are discussed as the foundation for WTLTP.

1.1. History of WTL

David Russell’s history\(^7\) of the WAC movement traced the cultural changes in the U.S. that enabled the movement’s growth. Until the 1960s, universities were focused on disciplinary rigor and
purity, so writing instruction was considered the domain of the English department. However, social change made the college classroom increasingly diverse, underscoring the need to provide more comprehensive writing instruction to students of all backgrounds and disciplines. WTL strategies were useful because they prompt students to write for their own benefit, making course material more meaningful. WTL is based on the premise that students learn through the act of writing, particularly when the writing assignments are short, informal, and designed to promote reflection, analysis, synthesis, and deeper understanding of course material. Examples of such assignments include journals, commentary, and reflections.

WTL strategies also allow students to assert more control over the way they learn. Emig explains this benefit: “One writes best as one learns best, at one’s own pace.” Butler and Winne assert that individualized learning is critical to individual success: “the most effective learners and self-regulating.” They define self-regulation as “a suite of powerful skills: setting goals for upgrading knowledge; deliberating about strategies to select those that balance progress toward goals against unwanted tasks; and, as steps are taken and the task evolves, monitoring the accumulating effects of their engagement.” If students are to be active participants in their learning, writing assignments must prompt self-analysis and reflection. Emig describes the simple act of reading one’s own writing as a valuable learning moment in which “information from the process is immediately and visibly available as that portion of the product already written.” Reviewing a set of writings collected over time, then, creates an opportunity to extend the learning process. Both instructors and students benefit from the act of collecting artifacts because they represent the changes and growth that accompany learning. When integrated in a purposeful way appropriate to a given discipline, WTL deepens student understanding, improves student engagement, increases retention, and makes students active participants in the learning process.

1.2 WTL and computational thinking
To understand the value of WTL strategies to computer science education, it is useful to examine the thinking processes involved in learning to program and the problems novice programmers tend to encounter. Davies defines “computational thinking” as a complex type of problem solving that requires creativity as well as “elegance and precision.” According to Soloway, the problem solving process is inextricably linked with the act of communicating understanding: “learning to program amounts to learning how to construct mechanisms and how to construct explanations.” George distinguishes computer science learning from learning in “humanity-based subjects” as the difference between “declarative content,” or facts, and content that involves “procedures, processes, algorithms and problem solving steps.” To program, students must think computationally, which requires critical thinking, reflection, revision, and communication ability.

The challenge for many is that computational thinking takes place in the context of a new, complicated language. According to Davies, the challenge for students trying to learn a new way of thinking is the language of programming itself: “a frightening world of semicolons and curly
braces whose secret meaning takes great pains to discover.” With this type of distraction, Davies asserts that students cannot undertake the serious problem solving that lies behind the language. While programming does require a programming language, computational thinking can be supported by writing in a student’s native language.

Research in computer science has demonstrated that students’ ability to effectively explain the meanings of code “in plain English” is correlated with their ability to program. Murphy et al.\textsuperscript{15} found that students who could not correctly explain sections of code also had difficulty developing their own code as the semester progressed. Corney et al.\textsuperscript{16} found that this issue carried on into the data structures class. They hypothesize that developing students’ ability to explain code in written English can improve their ability to develop code. Essentially, WTL principles can support students’ development of computational thinking skills by allowing them to think in their native language, thereby reducing a major barrier for learning to program.

1.3 WTLTP: A new genre in computer science education
The difficulty of teaching and learning introductory programming concepts is well documented. As early as the mid 1980s, the work of Soloway\textsuperscript{17} documented that only 14% of Yale’s CS1 students could solve a simple programming problem correctly. This study has been repeated over the years with similar results. At our home institution, for example, 42% of the students who have completed a two-semester programming class cannot solve the following program: “In a programming language of your choice, prompt the user to enter integers one at a time, keeping a running sum of the integers. If -1 is entered, then exit and print the sum.” Perkins and Martin describe the main deficit of novice programmers as “fragile knowledge…knowledge that is partial, hard to access, and often misused”\textsuperscript{18}. According to Lahtinen, Ala-Mutka and Järvinen\textsuperscript{19}, while most programming students can comprehend “basic concepts,” they struggle with “learning to apply them.” There is a significant need to address the well-documented and persistent need to improve programming pedagogy.

To improve programming pedagogy, we seek to re-introduce Knuth’s concept of literate programming in a significantly revised and improved manner. To quote Knuth, “Let us change our traditional attitude to the construction of programs: Instead of imagining that our main task is to instruct a computer what to do, let us concentrate rather on explaining to human beings what we want a computer to do.”\textsuperscript{20} The philosophy undergirding literate programming, succinctly stated, is that “you do not document programs (after the fact), but write documents that contain the programs.”\textsuperscript{21}

As educators, we believe that writing clarifies thinking, extends creative abilities, and enables effective communication. Our beliefs are backed by the aforementioned literature. Thus, our research goal is to explore how reflective writing intermingled with coding can enable students to more effectively develop requisite problem solving skills and learn how to program. We hypothesize that the interaction between writing and programming can significantly improve the develop-
opment of a novice programmer’s skills. Through writing, programmers can visualize their learning, allowing them to view the coding process as a series of logical, interrelated steps that connect an overall goal to all the potential ways of reaching it. In a broader context, this visualization could have far-reaching implications for professional programming. This fundamental shift in the programmer’s thinking requires a change in the programming process, particularly the process of learning to program.

We therefore propose a radical redesign of how writing and programming can and should interact, by making writing an essential component of programming instruction and the coding process as a whole. Specifically, embedding WTL strategies into the coding process will transform the way students learn to program. While students often view writing as separate from the practical demands of their professions, WTL strategies, when integrated purposefully, blend writing and learning in a way that can support development in any discipline and particularly in the context of programming, WTLTP leverages WTL strategies and intermingles writing with coding to support learner processes in an effort to improve programming pedagogy.

2. Writing-to-learn-to-program (WTLTP)
WTLTP represents a new genre built on the ideals of literate programming, which has rarely been incorporated into programming pedagogy. The purpose of WTLTP (and of literate programming) is not simply to add comments to code, but to transform a student’s thinking process, by making writing an integral step in every aspect of the programming endeavor. In addition to researching changes in student thinking and learning, we will explore the design of software and technologies that support WTLTP and programmer development in relevant learning environments.

2.1 WTLTP in the classroom
In a typical programming class, a lab assignment provides a problem specification; students are then graded on the correctness of their implementation. The bulk of instruction, therefore, focuses on teaching students to transform a problem into a specific implementation through a design-build-test cycle in which the design is accompanied by written artifacts such as a flowchart or pseudocode. The build process might also be accompanied by written artifacts (explain in English, for example), while the test process relies solely on the students’ expertise rather than taking any written form. The design-to-build process is typically a linear, one-time process—students are expected to iterate the build-test cycle based on their own abilities. Moreover, the written artifacts remain isolated from the program; while the code (and, implicitly, the design) may evolve during the build-test cycle, the written artifacts remain unchanged. This process poorly supports the student’s actual thinking process.

Therefore, we propose a method that matches and supports the ways students think about and solve programming problems, by intermingling writing throughout the design-test-build cycle. The WTLTP program is a document, which can and must contain all writing artifacts produced
throughout the process. These artifacts prompt students to describe their thinking processes and reflect on their learning throughout the cycle. Specifically, the process begins as the students craft a description of their design, capturing the overall flow of the program. Next, students write reflectively, considering how this design should be captured in specific coding constructs (loops, functions, etc.). The build step begins with students evaluating which specific statements to use (which is the best library function to call, or how to index an array), then coding that particular portion of the program. The coding informs the overall design; perhaps the constraints of the language as the implementation proceeds will change the design, prompting students to rewrite and rethink that portion of the document. Next, students execute the program, then record and reflect on the observations captured by this experiment: did the program follow the mental model the student had formed of the program? If not, how was that model incorrect? What then should be changed? If these written reflections change the design or build aspects, those can be updated as a part of making changes to the code.

As a concrete example, consider a typical programming assignment taken from CSE 1384, Intermediate Computer Programming, offered at our home institution. In this lab, students write a class to support basic operations on rational numbers, which are represented as two integers N/D (Figure 1). A set of requirements is given, and students must then solve the problem with little guidance on the thinking process that should accompany the problem. In contrast, the screenshots in Figures 2–5 illustrate the integration of writing throughout the process of crafting a solution to this problem. In a beginning lab, the literate programming paradigm carefully guides students through the writing and thinking process; later labs have less guidance, requiring more creative, independent writing and thinking.

2.2 Existing software supporting WTLTP processes

Knuth’s original literate programming system, consisting of the WEB (for the Pascal language) and CWEB (for C) applications, provide this needed ability, albeit with several significant drawbacks. First, CWEB’s input is not source code, but a document containing fragments of code mixed with troff/nroff or TeX/LaTeX and CWEB markup, requiring a steep learning curve and resulting in difficult-to-read documents for the uninitiated. CWEB then transforms this input into source code, stripping out much of the markup and formatting and rearranging the order, which produces source code that cannot be understood apart from laboriously referring to the CWEB document it came from. This makes use of a traditional IDE, along with the many tools it offers (debuggers, syntax highlighting, automatic refactoring, version control, static analysis, etc.), difficult if not impossible. Second, the typeset output of CWEB (typically a PDF document produced by compiling the literate programming input) is likewise difficult to edit. It cannot be directly edited; instead, the TeX/LaTeX fragment that produced it must be located by hand in the source literate program, then edited, then recompiled to a PDF document to check that the edits produced the desired typeset result. Although SyncTeX provides a mapping from a PDF paragraph to the underlying TeX/LaTeX that generated it, CWEB does not extend this mapping to
the literate programming source. In addition, though several excellent GUIs embed this synchro-
nization in a TeX/LaTeX environment (TeXWorks, for example, supports Windows/Linux/Mac),
none provide this for CWEB, imposing a high cost on editing the typeset output.

Although many other literate programming packages exist as reviewed by Schulte\textsuperscript{24}, Pieterse, V. et. al.\textsuperscript{25}, most share these same weaknesses: they take a literate program as input and produce
source code as output, creating relatively difficult-to-read code that cannot be directly edited be-
cause it will be overwritten by the next document-to-code transformation. Likewise, these pack-
ages take a literate program as input and produce a typeset document as output, creating beautiful
documents that are time-consuming to edit.\textsuperscript{26}

While literate programming tools have not entered the mainstream, their variants have; docu-
mentation generators, such as Doxygen and Javadoc, boast a huge user base and produce vast
numbers of web pages that document large libraries and applications, such as the Java API and
the KDE window manager. These tools provide an excellent method for documenting the exter-
nals of a program—its application programming interface (API), typically. However, from a lit-
erate programming perspective, these tools lack the ability to explain the inner workings of a
function or method, instead restricting themselves to documenting how to call a function but not
why the function works the way it does. Therefore, these tools likewise lack the ability for stu-
dents to explain in writing what they are doing and why they are doing it.
Literate programming techniques have been previously employed in the classroom, with most activity occurring in the 1990s. Hurst\textsuperscript{27} primarily investigates the tools needed to grade homework submissions, reporting that “the general quality of student submission has risen as a result of using literate programming” but offering little quantitative data in support of this assertion. Childs, Dunn, and Lively\textsuperscript{28} report “significant benefit from the use of literate programming,” providing detailed analysis that substantiates this finding. However, students reported frustration using the required literate programming tools (Emacs, TeX, and WEB). Shum and Cook\textsuperscript{29} employed a literate programming tool, reporting that students using the system wrote comments that described the algorithm used by the code; students using a traditional programming methodology did not write these comments. Unfortunately, students reported that debugging the code produced by the tool was very difficult. Again, while the literate programming approach demonstrably improves novices’ programming ability, the barriers raised by the current set of tools make these benefits difficult to realize. These barriers make the ability students most need—the ability

![Figure 2. The CodeChat user interface, showing the code view on the left synchronized to the document view on the right.](image)
to write before, during, and after they code—difficult if not impossible to learn.

2.3 CodeChat: Improved software to support WTLTP
With the goal of alleviating the weaknesses with current software described in section 2.2, we have developed a literate programming system named CodeChat. Figures 2–6 illustrate CodeChat’s implementation in its present form.

The series of screenshots (except Figure 5) show a WTLTP lab on rational numbers for CSE 1384, Intermediate Programming, which is taught in the Python programming language. Figure 2 can be compared to the current lab shown in Figure 1. The WTLTP lab consists of a series of unit tests that guide a student through the implementation of a rational numbers class. The Python source code that the student will edit is presented on the left side of Figure 2, while on the right side, this source code has been transformed into a document (a web page), providing a visual reminder to students that a program is a document and should be treated as such. (The current

![Figure 3](image_url)

Figure 3. The use of a program as a document which contains both descriptive and prescriptive portions.

implementation does not allow editing from the document view). The included GUI synchroniz-
es between source code and web output automatically, so that movement or mouse clicks in the source code editor shows the corresponding HTML text and vice versa. CodeChat interprets the comments of the source code using reStructuredText (ReST), whose primary goal is to “define and implement a markup syntax … that is readable and simple, yet powerful enough for non-trivial use” as described on reStructuredText homepage.

Figure 3 demonstrates the use of a program as document that contains both descriptive and prescriptive (i.e., executable) portions. Here the unit test passes only if a divide-by-zero exception is raised by student code. This helps focus novice programmers on solving one problem at a time. It requires them to fill in a portion of the document with the results of their successful test (so that students will not simply skip this step to their own detriment) and the code they used, while simultaneously providing an opportunity to reflect.

Figure 4 shows a set of embedded reflection questions requiring student responses. These questions help a student think about how best to implement rational number simplification before writing the code and require them to gain a deeper understanding of the library routine (gcd) they
will use. This helps students produce code that they understand, rather than code that “just sorta works” without deep understanding.

The program-as-document approach to literate programming in Figure 5 shows that intermingling images and equations with the code that implements them provides a natural, intuitive explanation of the operation of a quad-copter (a four-bladed rotary-wing aircraft). This approach allows students to think through the complex mathematics they must implement, or instructors to better convey the connection between theory and its implementation in a program.

3. Conclusions and future research direction
In this conceptual paper, we introduce a new genre in computer science pedagogy based on intermingling writing activities with coding. We have proposed a radical redesign of how writing and programming can and should interact. We contribute to WTL literature by incorporating WTL principles into a new domain. We build on Knuth’s initial ideas for literate programming by proposing the integration of those ideas into technology supporting learning and into class-

Figure 5. Intermingling images and equations with code demonstrates the program-as-document approach to literate programming.
room learning environments. We have established the background and need for the new WTLTP genre.

This conceptual paper is the precursor to our upcoming research investigation into the use of technology to facilitate WTLTP in the technology-rich environment of an introductory programming course. The purpose of our future research direction is to thoroughly investigate how WTLTP can help students learn to program. We focus on understanding the impact of WTLTP instruction on students’ programming development in comparison to students educated by traditional programming pedagogy. We also plan to investigate how WTLTP may impact students’ development as writers. Finally, we have planned data collection that will offer insight into “best practices” for effectively integrating WTLTP in classrooms. All of our research is driven by the overarching research question: How can intermingled writing assignments affect the development of a novice’s programming skills? Our research plan will allow us to consider 1) next steps for how technology can support intermingled WTL, 2) how instructors can support intermingled WTL, and 3) challenges to effective use of intermingled WTL in classroom contexts.

References


26 PyLit, available at http://pylit.berlios.de/index.html, represents the only tool known to the authors which also stores the literate programming source in the source file, lacks a GUI to synchronize between typeset output and source code.

