Evaluating A BASIC Approach to Sensor Network Node Programming

J. Scott Miller
jeffrey-miller@northwestern.edu
Northwestern University

Peter A. Dinda
pdinda@northwestern.edu
Northwestern University

Robert P. Dick
dickrp@eecs.umich.edu
University of Michigan

Abstract

Sensor networks have the potential to empower domain experts from a wide range of fields. However, presently they are notoriously difficult for these domain experts to program, even though their applications are often conceptually simple. We address this problem by applying the BASIC programming language to sensor networks and evaluating its effectiveness. BASIC has proven highly successful in the past in allowing novices to write useful programs on home computers. Our contributions include a user study evaluating how well novice (no programming experience) and intermediate (some programming experience) users can accomplish simple sensor network tasks in BASIC and in TinyScript (a principally event-driven high-level language for node-oriented programming) and an evaluation of power consumption issues in BASIC. 45–55% of novice users can complete simple tasks in BASIC, while only 0–17% can do so in TinyScript. In both languages, users generally are most successful using imperative loop-oriented programming. The use of an interpreter, such as our BASIC implementation, has little impact on the power consumption of applications in which computational demands are low. Further, when in final form, BASIC can be compiled to reduce power consumption even further.

Categories and Subject Descriptors

D.2 [**Software Engineering**]: Metrics; C.3 [**Special-Purpose and Application-Based Systems**]: Real-time and Embedded Systems

General Terms

Human Factors, Languages, Measurement

Keywords

BASIC, Cyber-Physical Systems, Sensor Networks

1 Introduction

Wireless sensor networks (WSNs) can be viewed as general purpose distributed computing platforms defined by their spatial presence and an emphasis on environment monitoring. The most prominent applications of sensor networks have thus far included monitoring applications with a variety of requirements, although WSNs need not be limited to these tasks. While WSNs are currently of great research interest, it is ultimately communities and users *outside* of these areas—application domain experts—that have the most to gain from the functionality that WSNs can provide. We focus on application domain experts who are programming novices and *not* WSN experts. Our goal is to make the development of WSN *applications* by such individuals and groups tractable and, ideally, straightforward.

To deliver the power of wireless sensor networks into the hands of such application domain experts, the barrier to entry must be modest. In terms of raw hardware, this point has already mostly been reached, provided custom hardware is not needed. However, through our interaction with a civil engineering group that is designing, implementing, and deploying an autonomous (structural) crack monitoring application [17, 9], we have become convinced that sensor network programming languages and systems have not yet reached this point. Current languages require knowledge of either very low-level systems development (including the details of sensor hardware and embedded system design), or high-level programming concepts and abstractions that are not obvious to most application domain experts. We have observed that application domain experts have little programming experience, most of which is with with simple single-threaded imperative programming models.

It cannot be assumed that an application domain expert who stands to benefit from a WSN possesses a background in embedded systems development, can devote time to a programming curriculum, or has the funds to hire an embedded systems expert. Even if such an expert is available, the capabilities of a sensor network are tightly coupled to its hardware and software design, making any disconnect between the application domain expert and embedded systems expert a barrier to achieving the domain expert's goals.

It is vital that application domain experts not be confused with traditional application developers. A Unix, Windows, or web developer may be able to stretch his capabilities to write a WSN application. For example, someone familiar with writing Microsoft Windows applications in C++ or C# already has some of the conceptual framework needed to grasp event-driven programming in a C-like language on a sensor network node. From our experiences with application domain experts in the broad area of structural crack monitoring, we have come to the conclusion that experts generally start with less programming background than application programmers. For this reason, it is unlikely that programming languages and concepts that have found strong adoption and demonstrated productivity gains in the WSN or general software development communities will give application domain experts similar results. We can only assume that the application domain expert will remain a perpetual novice[1], or, at best, an intermediate programmer.

To evaluate the programming backgrounds of domain experts, we conducted a survey of graduate students and faculty working both in the sensor network domain as well as domain experts in areas that can benefit from the monitoring capabilities of modern sensor networks. Our results, which we present in Section 3, show that while the sensor network experts generally have substantial programming experience across a range of general-purpose programming languages, domain experts reported limited experience with a smaller set of programming languages.

The sensor network research community has made several efforts to simplify the development of WSN applications by creating a range of languages and programming systems designed specifically for the platform (see Section 2 for more). These languages span a number of programming paradigms and each targets a different type of developer.

Our work continues and expands upon this direction by bringing less-experienced programmers, including application domain experts as previously described, into the core of the language design and implementation "loop" via rigorous user studies. We run user studies to (1) evaluate how our target users respond to different languages and systems, (2) determine how quickly and correctly they can complete tasks using each language and how power-efficient the solutions are, and (3) inform future language, system, and interface design for these users.

This paper reports on our efforts to apply user studies to the problem of making WSNs easy to program by application domain experts. We focus on the problem of programming individual nodes, including sensing, sending information back to a centralized aggregator, and node-based actuation. Although this problem is more limited in scope than general WSN programming, and the kinds of programming supported by other languages/programming systems, it is nonetheless an interesting problem as node-level programming has broad utility, especially for applications in which complex network communication, such as aggregation, is not needed.

Extrapolating from the undeniable success that the BASIC programming language had in the late 1970s and early 1980s in engaging extreme novices—even children—in programming, and the similarities between the home computer platforms of that era and the sensor network nodes of today, we consider the use of BASIC as a WSN node programming language. Our specific contributions follow.

- We surveyed domain experts and sensor network experts to compare their programming backgrounds.
- We ported a small BASIC interpreter to a modern sensor network node and OS, extending the language and implementation with easy-to-understand features for communication, power management, sensing, and actuation. The semantics of the language were refined using observations of the successes and struggles of novice and intermediate programmers using it.
- We created a simple integrated development environment (IDE) and tutorial for our extended BASIC, both targeting the kinds of users described earlier.
- We evaluated our extended BASIC, IDE, and tutorial by conducting a rigorous user study involving novice and intermediate programmers.
- We also evaluated TinyScript, a high-level, event-driven node-level programming language for sensor networks using exercises identical to those used to evaluate BASIC.
- We measured the computational and power costs involved in using our interpreter.

Beyond letting us evaluate the utility of our BASIC, the user studies noted above also provide a useful characterization of user reaction to TinyScript, and prototypes for future work.[2] We found the following.

- The programming background of domain experts is considerably different from that of sensor network experts. Their background is similar to the intermediate participants in our study.
- Novice users are able to use our system to implement simple sensor network programs on MicaZ motes that include data acquisition, communication, and actuation.
- While results are task-dependent, 45–55% of novice users are likely to complete simple tasks in BASIC, while only 0–17% are likely to do so in TinyScript.
- Participants with programming experience (intermediate users) had similar rates of success using BASIC and TinyScript.
- Many participants struggled with developing applications using an event-driven programming model.
- While our system incurs a significant computational overhead (the interpreted code is, not surprisingly, much slower than compiled C), for common application patterns in which the hardware spends significant time asleep, this overhead and its concomitant power costs are negligible. A "sense-and-send" task with a one second period consumes only 1.5% more power when written in BASIC. BASIC can be compiled to virtually eliminate this overhead.

This experience underlines the value of using user studies to evaluate languages and programming systems targeting application domain experts. Our work shows that there is

[1]We use this term in the sense meant by Dineh Davis [7] who argues that instead of searching for ways to make users experts in the use of computers and technology, we should seek ways to make them better novices.

[2]See http://www.absythproject.org/ for study materials.

value in using BASIC-like languages in the sensor network domain and more broadly identified some of the language features most appropriate for enabling novice programmers.

2 Related Work

The architectural visions of Hill et al [14]; Polastre, Szewczyk, and Culler [32]; as well as Cerpa and Estrin [4] have had great impact on sensor network research and design. Our work is more specifically related to work on sensor network programming languages, measures of software engineering productivity, and existing applications.

Sensor network programming languages: There are a number of programming languages, support libraries, and operating systems for sensor network nodes [12, 24, 1, 22, 5, 20, 11]. They provide support for modular programming and the use of hardware modules, reaction to events, and some degree of network abstraction. Some languages focus on permitting specification of network-wide behavior instead of specifying the behavior of individual components [13, 28]. Bonivento, Carloni, and Sangiovanni-Vincentelli propose a platform-based design methodology for wireless sensor networks [3]. Recent improvements to sensor network programming environments have been substantial. However, these advances primarily benefit embedded system design and programming experts, not application domain experts.

Existing sensor network programming languages are designed to ease the development and deployment of sensor applications. The languages borrow their semantics from well-known programming paradigms, including structured query, functional, and event-driven styles. The languages differ in the abstraction they provide for the underlying sensor network, treating the network as either a single logical machine or a collection of communicating entities.

The Regiment [27], TinyDB [25], and Tables [16] languages are examples of macro-programming languages in which the developer writes code that targets the entire sensor network. Heterogeneous execution emerges based on local conditions. Regiment follows a functional programming design that treats each sensor as a stream of data. Regiment allows programmers to partition streams into logical neighborhoods based on network proximity, allowing event detection that spans multiple sensors. In TinyDB, the programmer writes queries to a logical database table representing sensor values across the network. TinyDB's SQL-like syntax is assumed to be familiar to application developers. Tables, a framework for programming sensor networks that uses a spreadsheet model (specifically, pivot tables) to describe tasks, takes a similar approach.

MacroLab [15] is a recently developed Matlab-like, vector-based, macro-programming language for sensor networks. Its macrovector data primitive is a matrix data structure in which the index in one dimension is the sensor node. Data collection and aggregation operations are specified using familiar Matlab matrix operations. To simplify the choice of data dissemination model, the MacroLab toolchain optimizes the extent to which computation is distributed according to a user-supplied cost function, partially separating task specification from implementation; however, the programmer must still specify which operations must be synchronized across the network. Given the relative common familiarity of domain experts with Matlab (Section 3), MacroLab is likely to be a good fit for domain expert-programmed applications that demand complex network behavior.

In contrast to such network-level languages, NesC [14], TinyScript [23], and C (with WSN support libraries) are node-level programming languages, targeting individual sensors. In practice, however, the model is SPMD (Single Program Multiple Data)—the same code generally runs on all the nodes in the network with the possible exception of a base station that acts as an accumulator of sensor data. All of these languages provide an imperative syntax. In both NesC and TinyScript, high-level program flow is controlled through events that are triggered by communication, timers, or are user-defined.

Aside from their scope, these node-level languages target different kinds of programmers. The C-like syntax of NesC is more appropriate for programmers with strong C backgrounds. NesC also uses a form of event-driven programming that seasoned developers might be accustomed to but is unfamiliar to a large class of novice programmers. TinyScript adopts a more simplified set of semantics in order to make the NesC model more approachable for novices.

In addition to these node-level languages, higher level application programming languages have also made inroads on the WSN space. The Micro .NET Framework [26] and Sun SPOTS [34] platforms leverage the C# and Java languages, respectively, which should be familiar to a range of experienced application developers.

The present work focuses on node-level programming languages and systems for *novice users*, including application domain experts. For the most part, the network-level and node-level languages just described have the goal of making *expert developers* more efficient. The exceptions are TinyScript (node-level), on which we elaborate below, Tables, and MacroLab. Tables specifically targets inexperienced users, and MacroLab can arguably support them. In contrast with our work, however, Tables and MacroLab are network-level programming system, and, to the best of our knowledge, have not yet been evaluated in user studies.

TinyScript: The goals of the present paper most closely resemble those of TinyScript [23], a high-level programming language that is compiled to the byte-code of the Maté virtual machine platform for sensor networks [22]. TinyScript is described as "an imperative, BASIC-like language with dynamic typing and basic control structures such as conditionals and loops." [21] The creators of TinyScript were early to expose the interesting problem that we are now working on: how can one design a language to make sensor network programming more accessible? Their answer, TinyScript, is a dynamically typed, event-driven imperative language. TinyScript applications result in relatively few high-level Maté instructions, allowing for straightforward application distribution and updates within a sensor network.

Our work differs from TinyScript in several ways. First, BASIC is a simple imperative language with no event model. We have added extensions to support node-level programing. Our implementation is a simple tokenizing interpreter (which leverages the uBASIC codebase of Adam Dunkels [10]) with no underlying byte-code virtual machine.

A second difference is that we have focused, both in the language and in the presentation of the language via the IDE, on reducing complexity for shorter programs. A program in our system is represented as a single source code file, displayed (and hidden) in a custom IDE. All control flow is in this file and is immediately visible to the programmer. In contrast, in TinyScript, the programmer creates a separate code block for each handled event, with code in one handler being able to interact with that in another. The TinyScript IDE further separates each event handler by allowing the programmer to view and modify only one handler at a time. There is no notion of scope in our BASIC—all variables are at global scope. In contrast, variables in TinyScript are either locally scoped to each event handler or globally scoped across all handlers. All variables in our BASIC are either integers or arrays of integers. In contrast, in TinyScript, data is represented by several types and the application developer must at times explicitly convert among types.

TinyScript's event-driven model does allow for more complex data aggregation techniques than we explore in this work. Functions are provided for broadcast and base station communication that can, with some care, be used to implement in-network aggregation. However, it is unlikely that this abstraction is adequate for specifying applications with substantial data aggregation. In contemporaneous work [2], we found that inexperienced programmers struggle to apply these abstractions to WSN applications with simple aggregation. In this work, we focus on node-level operation with simple, base station oriented communication.

The extreme simplicity of BASIC makes it unsuitable for the development of large software projects, and event-driven control flow, scoping, and typing should be minor issues for an experienced application developer. However, WSN nodes are very resource constrained, so large software is physically impossible, and our target user is the novice, for whom events, scoping, and typing are challenges.

We show here how these differences affect application development for novice and intermediate users by carrying out user studies comparing BASIC and TinyScript. We initially considered a comparison against NesC, but it quickly became clear that it was unlikely that novice or intermediate programmers would make much progress completing tasks in the time generally available in a user study. In comparing two languages, it is difficult to precisely quantify the effect of different aspects of the programming model and the language semantics on programmer efficacy, potentially conflating the two. In our study, we provide qualitative observations based on collected screen-captures to help alleviate this issue.

Evaluating our system with novice and intermediate users is a key component of our work. We have intentionally sought out such users to understand how well our design succeeds at enabling sensor network development by them, and to inform future language improvements.

Archetype-specific languages: In contemporaneous work [2], we surveyed a large set of existing, deployed sensor network applications and clustered them to arrive at a set of seven sensor network application archetypes. These archetypes capture applications with a range of complex network behaviors that are generally best captured in network-oriented languages. We advocate the creation of a language for each archetype. However, there is a significant set of applications for which a node-oriented programming languages, such as our BASIC, are well suited. Such applications are typically homogeneous systems requiring periodic or event-driven sensing, actuation, and limited aggregation.

	Response — average (stddev)	
Question	Domain Experts	WSN Experts
Count	4	7
Largest program written (LOC)	600 (935)	93,614 (182,558)
Largest program modified (LOC)	413 (440)	156,286 (154,132)
LOC changed/added	81 (146)	3,357 (5,419)
Number of languages known	4 (2.6)	8.9 (2.5)
Familiarity with them (Leikert)	4.2 (1.9)	5.1 (1.5)

Figure 1. Programming background survey.

Productivity measures: Although a range of software engineering metrics exist [18], we are unaware of any proposed metric or benchmark for sensor network application programming by novices. Work developing metrics for evaluating students in introductory programming courses [8] is related, but doesn't consider the power concerns and environmental coupling of sensor network applications.

All of the sensor network programming languages and systems discussed earlier include abstractions whose aim is to simplify the process of writing code. Across this varied landscape of languages, there is little quantification of how well each language suits the needs of different user communities, particularly application domain experts acting as novice programmers. As far as we are aware, there is no agreed upon set of benchmarks to assess the strengths or weaknesses of each language. This degree of choice is common among languages targeting expert programmers, but likely overwhelming for novices. Our work includes the rudiments of an evaluation strategy that could provide data for ranking systems in terms of their utility for novices.

3 Experience of Domain Experts

A natural question that arises when attempting to target domain experts, as we do, is what the programming skillsets of such experts are. Our choice of BASIC, the design of our study, and the selection of participants is informed by our intuition that many domain experts have limited programming experience, and what programming experience they do have may not map well to sensor networks.

To evaluate this intuition, we created a 10 minute online survey that attempts to quantify programming background.[3] The survey asked respondents about their programming background, including the size of the largest programs they have written. The survey also solicits familiarity with a range of programming languages and allows the respondent to add any additional languages that they have encountered. We then asked our colleagues at five institutions to complete the survey and forward it to others working in sensor networks. The survey was completed by both sensor network experts and application domain experts.

Figure 1 shows the results of the survey. The most important observation is that there is a stark difference in pro-

[3]We considered using programming aptitude tests [30], but such tests are quite dated, controversial, and/or too cumbersome.

gramming background between sensor network experts and domain experts, with domain experts having far more limited programming experience in terms of languages, programming styles, and lines of code written. Three of the domain experts reported largest program sizes of 200 lines of code or less. The domain experts surveyed reported programming experience in a small number of imperative languages, with MATLAB the most popular (3 participants), followed by C, C++ and Fortran.

The domain experts in the survey roughly correspond to the intermediate users in the study that we describe in Section 6.1, and the structural monitoring domain expert implementation work described in Section 6.3. While the domain experts surveyed have more programming experience than the novice users in our study, the use of the feedback from the novice users was invaluable for improving the language.

4 Why BASIC?

As its name implies, the Beginners All-purpose Symbolic Instruction Code (BASIC) is specifically designed to provide programmers with a language that is complete, simple and easy to understand [6]. A grammar for early versions of BASIC confirms this: the language does not contain features now considered necessary for the creation of large, maintainable applications such encapsulation, user-defined types or in some cases even local variables.

Why then should we give users a programming language that is primitive when compared to its more modern peers? Many programming constructs have come about to promote code maintainability as an application grows in size. For sensor network applications characterized by relatively simple high-level behavior, such features are not necessary. Maintainability of tiny code bases is often easy in any language.

The simple syntax offered by BASIC minimizes the number of concepts that need to be understood by the novice programmer. The work of Van Someran [33] suggests that successful programmers must understand the execution model of their languages and BASIC has what is arguably one of the most simple execution models. Application domain experts view programming sensor nodes as a means of conducting a single aspect of their research. Given this, they have minimal time to spend in learning programming concepts, particularly if those concepts are not critical for the typically small programs they write. Furthermore, if the frequency at which they program is low, domain experts may forget programming concepts before reusing them. Thus it is vital that domain experts be able to quickly "context switch" into programming, even if they haven't used those skills in some time. BASIC's extreme simplicity has the advantage of making this easier.

It is important to indicate what specifically we mean by BASIC. Although its original developers, John Kemeny and Thomas Kurtz, feel that the language has been corrupted since its origins at Dartmouth in the 1960s [19], it is probably more accurate to say that BASIC has come to refer to an extremely widely varying family of languages. We are interested in the minimal, interpreted form of BASIC that emerged on home computers in the late 1970s. Those early 8-bit "microcomputers" were resource-constrained in much the same way as modern sensor network nodes. At its most minimal this was TinyBASIC [31], which is essentially the base language of the work described here.

5 Implementation

Our platform is based on uBASIC [10], an open source BASIC interpreter developed by Adam Dunkels and available under BSD license. uBASIC is written in C and is designed for embedded systems. The grammar of uBASIC resembles that of the TinyBASIC programming language. As described previously, TinyBASIC is a simplified dialect of BASIC designed for resource constrained computing environments and provides only simple programming constructs. We chose this variant of BASIC because its small memory requirement enables us to target a wide range of sensor platforms. Dunkels' web site indicates that uBASIC is eventually intended for use in "adding a simple scripting language to severely memory-constrained applications or systems (e.g. a scripting language to the web server applications in uIP or Contiki)." Our purpose is to see whether novice programmers can write simple sensor network node applications using an appropriately extended BASIC.

We ported the core interpreter to the Mantis Operating System [1], a sensor network operating system that provides a consistent API for reading sensor values, network communication and threading. The original code combined with our extensions spans approximately 2,000 lines of code. After compilation for the Crossbow MicaZ, our interpreter occupies 38 kB of flash. For comparison, an empty Mantis application has a 29 kB footprint when compiled with the same libraries. Our implementation is sufficiently compact that we may later add more complex protocols for routing and power management. Language and feature extensions prompted by our user studies are described in Section 6.2. The interpreter must be programmed directly through the serial connection. This allows for rapid development but limits the extent to which motes can be reprogrammed after being deployed.

Language design and extensions: We extended the BASIC grammar to include statements necessary for sensor network applications. Reading sensor values occurs with the SENSE statement, which take an expression indicating which sensor to read from (onboard MicaZ sensors are supported) and the name of the variable in which the value is to be stored. An analogous ADC statement is included for reading arbitrary ADC channels. The SENSE and ADC statements follow the semantics of the INPUT statement found in almost all BASIC implementations.

The LED statement controls the onboard LEDs on the platform. The LED statement is followed by a number specifying which LED is being manipulated and an expression indicating if the LED is to be turned on or off. A similar BUZZ statement exists to control the sounder found on many Crossbow sensor boards. A general DAC statement allows for arbitrary actuation control.

The SLEEP statement allows the programmer to halt operation for a desired duration. SLEEP directly maps to the thread sleep function provided by Mantis OS, which puts the mote into a low-power state when no thread is scheduled to run. The SLEEP statement is followed by an expression indicating how long the mote is to sleep, given in milliseconds. As we will discuss later, it is critical that the novice programmer understand the SLEEP statement.

To facilitate debugging, simple syntax checking is provided through error messages sent to the serial port. The user can also debug using the PRINT statement, which outputs the given expression list to the serial port.

We expose one-hop communication in the form of the SEND and RECEIVE statements. SEND mimics the functionality of PRINT, but communicates the data using the radio on the mote. The user can construct a message string to be broadcast using a combination of static text and integer expressions. The RECEIVE statement listens for messages sent with SEND. It mimics the BASIC INPUT statement. In our studies, we do not expose RECEIVE to the user but instead use it to implement base station functionality.

In response to the user studies, we made several substantial changes to our BASIC implementation, described in 6.2. These changes would not have been made without observation of the study group and the code they produced.

Development environment: We have created a simple integrated development environment (IDE) for programming the sensor. When programming, the sensor is attached to the development machine via the serial port. When running, the sensor is detached, and the IDE serves to print messages received from sensors. Our interface has three main components. The first is a field labeled "BASIC Code" that is used for entering and editing user programs. The second field, "Mote Output" displays any messages produced by the PRINT command as well as any syntax errors generated by the program. This information comes from the serial port-connected Mote. The final field, "Base Station Output" displays any messages broadcast using the SEND message. These are received using a Mote acting as a promiscuous listener. The programmer may run and stop their application from the environment's menus.

We deliberately designed our IDE to allow novices to program the motes without complication or external assistance. In studying the efficacy of BASIC, we did not want the development environment to be a distraction or source of failure. Furthermore, we wanted our user study to be runnable without proctor intervention. Our intention with the study is to focus on the difficulty of the programming language and thus our interface does not provide additional support in the form of code completion or line-by-line debugging. We did not detect usability problems with our user interface during experimentation.

6 Evaluation

The goals of our evaluation are (1) to assess the ease at which novice and intermediate users can develop correct and power efficient simple sensor applications in both BASIC and TinyScript, and (2) to determine the power and computational overhead of BASIC.

We addressed the first goal by conducting a user study on a population of novice and intermediate users, attempting to mirror the "worst case" of application domain experts. Half of users with absolutely no previous programming experience were able to complete simple sensor network tasks in

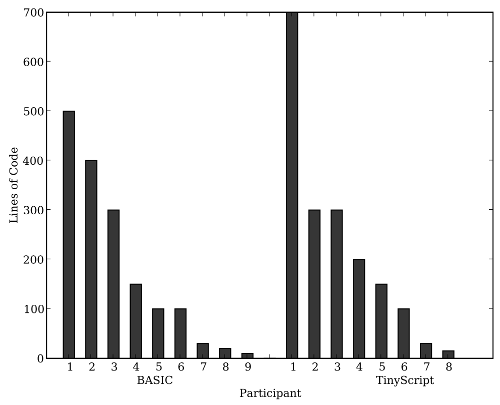


Figure 2. Largest program sizes for intermediate users in our two study groups. An additional 23 novice users had no significant previous programming experience.

BASIC, while that same category of user had much less success with TinyScript. Further, we found that novice and intermediate programmers both struggle with the event-driven model provided in TinyScript. To address the second goal, we directly measured power consumption as a function of desired compute rate, comparing a BASIC implementation with a C implementation. We found that interpreted BASIC is, of course, considerably slower than C, and thus has a far more limited maximum compute rate. Further, the power consumption costs grow much faster with increasing compute rate than C. However, for low rates, the two are quite comparable. For example, for a "sense and send" application running at a rate of 1 Hz, BASIC has only a 1.5% power overhead compared to C. Finally, we show that a compiled version of BASIC has a power profile similar to compiled C.

6.1 User Study

To study the ease with which novices can use both BASIC and TinyScript to write simple sensor network applications, we conducted a user study with 40 participants.[4] We recruited participants from a population of current and recent graduate and undergraduate students at Northwestern University, specifically targeting persons with little to no programming experience. Our population includes a mix of students with concentration in both the sciences and liberal arts, and includes roughly equal numbers of participants we consider *novice users* and *intermediate users*. Novice users have no programming experience, while intermediate users have some programming experience and training. Most intermediate users learned to program from classroom instruction. Users were randomly assigned to BASIC or TinyScript. Figure 2 illustrates the size of the largest program written by each of our intermediate users, and shows that that similar participants were assigned to each language.

For the BASIC study, there were 11 novices and 9 intermediate programmers while for the TinyScript study there were 12 novice and 8 intermediate programmers. The re-

[4]The study's human subjects research protocol was approved by our Institutional Review Board, which permitted us to recruit participants from a large and diverse pool, and to pay ($15) for their time.

sults we report here are summarized according to these experience levels, so the slight difference in the composition of the population sizes between the two languages is irrelevant. Among intermediate programmers in both groups, the most commonly reported languages with which the participant had previous experience were "C/C++" (9 participants), "Java/C#" (6 participants), and "Matlab" (6 participants).

6.1.1 BASIC Experimental Setup

Our experiments were carried out using two Crossbow MicaZ motes connected to a single desktop PC running Windows XP. During the study, our software is the only application visible to the user. Adjacent to the setup is a desk lamp the user needs to complete the study. Only one of the motes could be directly programmed by the participant while the other acted as a base station for receiving data sent from the participant's program. The BASIC interpreter is directly programmed via a serial connection to the mote throughout the experiment.

At the beginning of the study, each participant is presented with a tutorial document explaining the BASIC programming language and the sensor hardware. The tutorial is broadly written to cover the entire BASIC grammar, including such topics as variables and control flow. Additionally, the sensor network extensions supporting communication and reading sensor data are described.

Unless care is taken, the results of a study such as this may be influenced by the quality of the tutorial. Before we collected the results presented here, we conducted a preliminary study evaluating the clarity of the tutorial and iteratively improved on its design after each study. After evaluating the tutorial using three participants, we found it sufficiently clear for use.

Participants are given 30 minutes to familiarize themselves with the language and programming environment. During this time, they can use the IDE and mote to test program examples from the tutorial. Participants are not permitted to ask questions about the tutorial. Once the tutorial is completed, we ask the participant to fill out a questionnaire asking how difficult the tutorial was to follow, how well the participant understands BASIC, the clarity of the tutorial examples, and whether or not the tutorial should be longer. The next section discusses the questionnaire results.

After this questionnaire is filled out, three exercises are given. We give the participant 20 minutes to complete each exercise. The exercises and tutorial are designed such that no example code in the tutorial can be easily transformed into an exercise solution. In this way, the set of exercises is non-trivial and forces the participant to apply the language primitives learned in the tutorial to succeed. Each exercise requires the use of at least three language features such as sensing, duty cycling, and communication.

The exercises follow. Efficient solutions are illustrated in Figure 3.

1 The user is asked to write a simple program that blinks one of the LEDs on the sensor hardware at the rate of 1 Hz. This tests the user's understanding of basic node programming and the use of actuation. A solution to this exercise is possible with 4 to 5 lines of code.

2 The second exercise asks the user to write an application that sends a message to the base station when a desk lamp next to the user is turned off. This exercise requires that the user understand BASIC control flow, base station communication and reading data from the sensors. The exercise instructs the user to write power-efficient code and that a response time of 1–2 seconds is adequate.

3 The final exercise transforms the second into an actuation task in which an LED on the sensor is controlled by measuring the ambient light. In the exercise, the user is instructed to illuminate an LED on the mote if the desk lamp is turned off. Other than this change, the exercises are identical.

After the participants complete the exercise or time expires, we ask them to fill out a questionnaire describing the experience, soliciting how well they understood the problem presented, the quality of their solution and the extent to which they felt frustrated throughout the exercise.

Throughout the tutorial and exercises, we periodically take a snapshot of the user's program to provide insight into the process of development and to identify any stumbling blocks. The final program is also saved so that we can independently validate each solution and test its quality.

6.1.2 TinyScript Experimental Setup

We evaluate the TinyScript version distributed with TinyOS version 1.1.15. Our experimental setup for evaluating TinyScript is nearly identical to that used in the BASIC study. The changes result from differences between the two development environments.

The TinyScript evaluation used the same PC as that in the BASIC study, running a version of Ubuntu Linux in a VMWare hosted virtual machine.[5] While it is reasonable to suspect our participants are more familiar with Windows XP, no part of our study had the participants interacting directly with operating system-level user interface and thus we feel that the change does not influence our results.

We designed our TinyScript tutorial using existing tutorial documents created by TinyScript's authors. We edited these tutorials into one cohesive document, elaborating on certain concepts to make them more suitable for extremely inexperienced programmers. Further, we changed the tone and structure of the tutorial to match that of the BASIC tutorial, making exceptions to increase the clarity of the language. As with BASIC, we iterated on the TinyScript tutorial using participants recruited from the same population used during the final study as to maximize the tutorial's clarity. In all, five participants were used. We also made a copy of the tutorial available to the original author of the TinyScript materials.

Any study comparing two languages for programmer efficacy is subject to differences in the educational materials available for each language. We have made a significant effort to ensure similar quality materials through the means described above, and by seeking comments on the TinyScript materials from the language authors. Our materials for both languages are available online.

The remainder of the study, including the time allocated

[5]Existence of the VM is invisible to the user.

```
10 led 1 0
20 sleep 1000
30 led 1 1
40 sleep 1000
50 goto 10
```
Exercise 1

```
10 sense 0 a
20 if a < 800 then send "light off"
30 sleep 1000
40 goto 10
```
Exercise 2

```
10 sense 0 a
20 if a < 800 then led 1 1
30 if a > 800 then led 1 0
40 sleep 1000
50 goto 10
```
Exercise 3

Figure 3. Example efficient solutions for the exercises.

to the tutorial and exercises and exercise ordering, was unchanged for the TinyScript group.

6.1.3 *Results*

Tutorial questions: Following the tutorial, we asked participants in each language study group to rate their experience with the tutorial by rating their degree of agreement with four statements. We used these questions to get a sense for the participants' response to the language, independent of their performance on the exercises. The four follow: "I felt the tutorial was easy to understand," "I feel that I understand [the language]," "I followed the tutorial and tried many of the examples," "I feel that the tutorial should be longer." A standard Leikert scale ranging from 1 to 7 was used here and in all noted figures. 1 corresponds to "strongly disagree" and 7 corresponds to "strongly agree." The results for each of the prompts are given in Figure 4. They are broken down by language, and by novice and intermediate users. The graphs are standard Box plots showing the distribution of responses (25th, 50th, and 75th percentiles), with outliers shown individually.

Overall, we find similar trends across both languages. Participants show slightly less confidence with TinyScript as indicated by their response to "I felt the tutorial was easy to understand", with inexperienced TinyScript programmers giving the lowest ratings. Novice programmers using TinyScript indicated slight agreement with the prompt "I feel that the tutorial should be longer". We attribute these differences to the difference in complexity between the two languages. Because the wording of the question did not differentiate between the difficulty of the concepts and the clarity of their descriptions, we suspect that participants conflated those two concepts, resulting in lower ratings for the TinyScript group.

User experience of tasks: After working on each exercise, we asked participants to rate their experience levels. For each exercise, we asked the following questions, using the same scale used in the tutorial questions: "I understood what the exercise was asking me to do," "I was able to complete the exercise in the provided time," and "I felt frustrated throughout the exercise." In Figure 5 we present these results. For the first question, we see similar results between the two languages, indicating that the communication of our exercises does not seem to have introduced additional variation between the languages. However, in the remaining questions we begin to see more differentiation between the BASIC and TinyScript programmers.

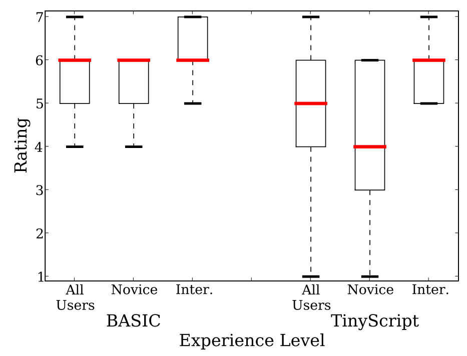
Measured performance on tasks: In Figures 6(a)–(d), we present all data about the measured performance of users in our study, as well as summaries by language and expertise. As Figure 6(a) shows, all intermediate BASIC programmers were able to complete at least one of the exercises.

In examining the BASIC solutions provided by participants, we discovered a common error in exercise 2 in which participants reversed the usage of the PRINT and SEND statements. Recall that the semantics of the two statements are nearly identical, producing output in either a "Base Station Output" panel in BASIC IDE in the case of the SEND statement or a nearly identical output window labeled "Mote Output" in the case of the PRINT statement. We attribute the confusion between the two statements to this subtle distinction in our user interface that fails to highlight the differences in medium. We note solutions that use the PRINT statement instead of SEND but are otherwise correct in the column titled "Correct (PRINT)." As will be discussed, many participants using TinyScript experienced an identical confusion while attempting to complete the second exercise.

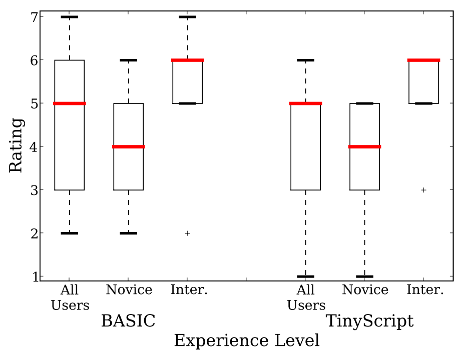
Intermediate programmers: Ignoring errors caused by this confusion, we find completion rates for intermediate programmers in BASIC were 100%, 89%, and 67% for exercises 1, 2, and 3, respectively. In Figure 6(b), we present the comparable results for the intermediate programmers using TinyScript. For the first and third exercises, the group performed approximately as well as their counterparts using BASIC, with correct solutions provided by 100% and 57% of the participants. However, this trend does not continue for participants attempting the second exercise, in which none of the TinyScript users were able to provide correct solutions.

Inspection of participants' solutions for exercise 2 reveals that many struggled with using the array abstraction provided by TinyScript. Use of the arrays are required for completing the exercise as the communication functions provided by TinyScript exclusively use array arguments. While this fact makes direct comparison between BASIC and TinyScript problematic for this exercise, there is nonetheless something to be learned from the manner in which users struggled. The array data structures provided by TinyScript appear to have been designed to simplify their use: the arrays are of a fixed size (10) and provide a shorthand for push and pop operations, giving the structure the feeling of an array-stack hybrid. Many participants struggled with this functionality, creating solutions that would often cause the array to overflow. In Section 6.2 we discuss how we use these findings to influence our implementation of arrays in BASIC.

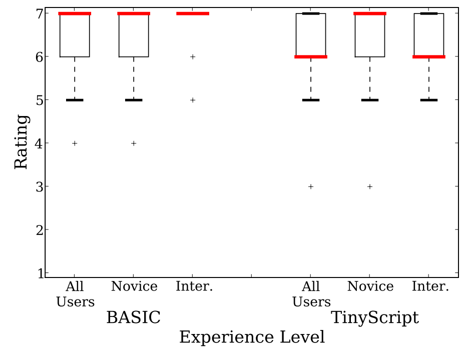
The confusion regarding the distinction between serial and wireless communication was also visible in the TinyScript group. Analogous to the PRINT and SEND statements are uart() and send() functions. Similar numbers of participants confused their use as in the BASIC study, though no participants were able to provide a solution that was otherwise correct.



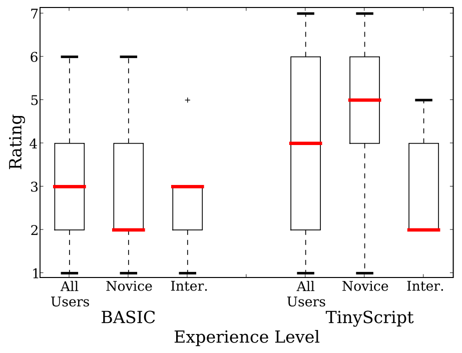
(a) “I felt that the tutorial was easy to understand.”



(b) “I feel that I understand [the language].”



(c) “I followed the tutorial and tried many of the examples.”



(d) “I feel that the tutorial should be longer.”

Figure 4. User responses to prompts given after completion of tutorial. A rating of 1 corresponds to “strongly disagree” and 7 corresponds to “strongly agree”.

Finally, we find that both groups were able to provide efficient implementations at similar rates. Efficient implementations are those that use each language’s (either implicit or explicit) abstractions for power management.

Novice programmers: We now draw our attention to the ability of novice participants to complete the set of exercises. We report these results for BASIC and TinyScript in Figures 6(c) and (d) respectively. Here, the contrast between the two languages becomes much more pronounced. For the first exercise, 54% of participants using BASIC were able to complete the first exercise, whereas none of the participants using TinyScript could do so. Likewise, 45% of the BASIC participants completed exercise 2, while none of the TinyScript participants succeeded. Finally, 17% of the participants using TinyScript had success with exercise 3, compared to 46% of the BASIC group. Overall, on the order of *half of the novices—people who have never programmed before in any language—were able to produce good solutions in BASIC*, a considerably larger fraction than with TinyScript.

We attribute the different rates of success between the two groups to the relative complexity of the TinyScript language. Each additional language feature (e.g., data types, event-driven control flow, etc.) imposes a real cost on the novice developer, complicating their mental model of the program’s execution. Given the typical programming background of our intermediate participants, it is likely that they have previously encountered topics such as types and variable scope.

Outside of the coarse categorization of “correct” versus “incorrect” solutions, we observed another interested phenomenon: few solutions submitted by the participants in either experience group used TinyScript’s event model. In TinyScript, the programmer has access to two timer-based event handlers. The period of the timers would be specified in the “once” event handler that is analogous to the “main” function in a C program. Instead of placing code in one of the timer-based handlers, participants would write all of their code in the “once” handler, placing the desired functionality into a non-terminating for loop. Only 3 out of the 15 total correct solutions across all of the TinyScript exercises used the event-driven model. Informal interviews held after the completion of the exercises suggested that participants did not understand what would happen to the application state after either the “once” or timer-based handlers terminated. It is not likely that this was an artifact of the presentation of the language. Our TinyScript manual gives equal weight to both approaches, and even provides an example of a periodic TinyScript program.

Overall, our studies show that our extended BASIC allows for novices who have never programmed before to complete simple sensor network applications after a short tutorial. We have also found that both novice and intermediate programmers struggle with the event-driven model provided by TinyScript.

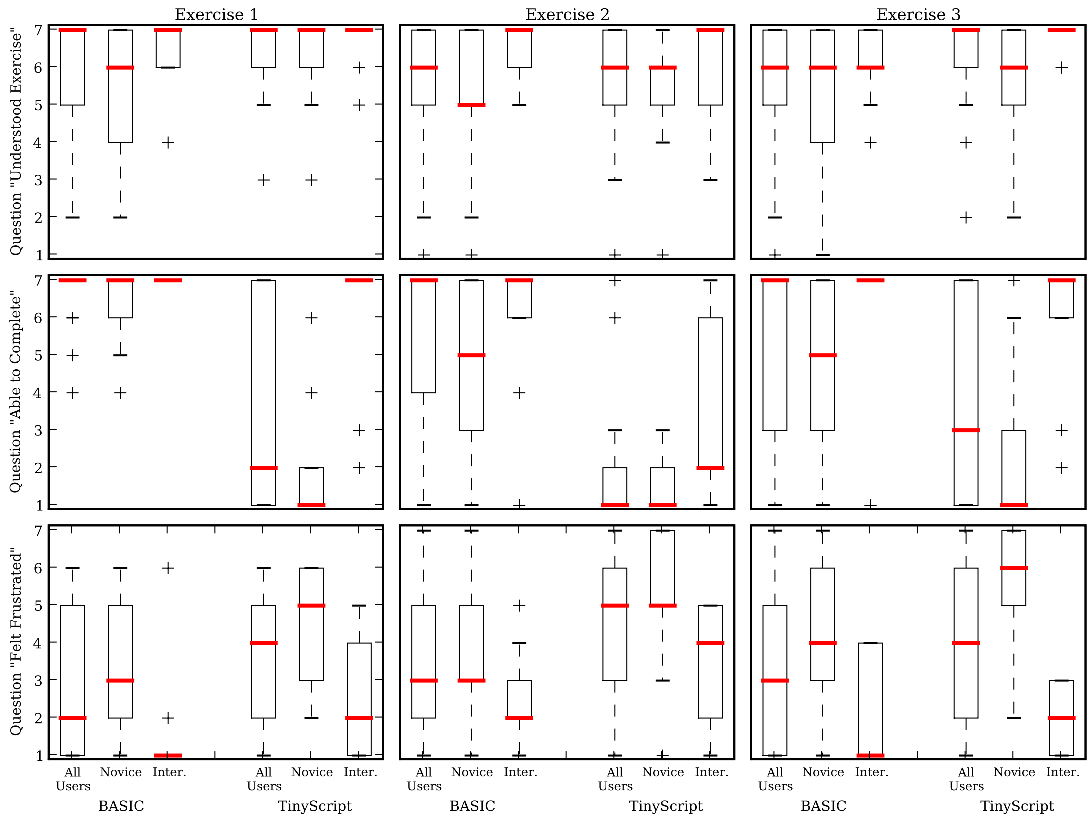


Figure 5. User responses to a set of prompts given after each exercise. Columns correspond to different exercises while rows indicate the question being answered.

```
10 sense 0 a
20 if a < 800 then led 1 1
30 sleep 2000
40 if a > 800 then led 1 0
50 sleep 2000
60 goto 10
```

Figure 7. One participant's solution to exercise 3. The extra SLEEP statement indicates a misunderstanding of proper duty cycling.

```
10 sleep period 1 sec
20 sense light into a
30 if a < 800 then send "light off"
40 resume
```

Figure 8. An example solution to exercise 2 using the periodic sleep language extension made in response to feedback from the user study as well as several refinements to the BASIC grammar.

6.2 Language Modifications

In examining the code produced by our study participants, we found participants in both the BASIC and TinyScript groups that either neglected to duty-cycle their applications or did so in such a way that introduced unnecessary delay to event detection. An example of this can be seen in Figure 7.

In response to this issue, we designed and implemented a simple extension to our BASIC interpreter to facilitate the kind of duty-cycled applications common in WSNs. The language extension adds the PERIOD keyword which can be used as a modifier to the SLEEP statement along with RESUME, a new statement that takes no arguments. An example of how this statement can be applied to exercise 2 can be found in Figure 8. Should the execution time of the code between the SLEEP and RESUME statement extend beyond the given period, the interpreter issues a warning.

We also added array data structures to the uBASIC language. Arrays variables are declared using the DIM keyword followed by an array size enclosed in angle brackets. Our decision to explicitly require that the programmer specify array size at allocation time and limit array accesses to by-index comes from watching users struggle with array indexing using TinyScript. To support applications requiring the manipulation and reporting of large data sets, arrays can contain as many as 65536 elements. The interpreter will transparently page the arrays to flash as needed.

To support high-resolution sampling, we extended the syntax of the SENSE statement to support several additional keywords. These allow the user to specify a desired sampling rate along with the number of samples to collect at that rate. The interpreter then ensures that the samples are collected at the correct sampling rate, issuing a warning if the

	Exercise 1			Exercise 2				Exercise 3			Total	
Subject	Correct	LoC	Efficient	Correct	Correct (PRINT)	LoC	Efficient	Correct	LoC	Efficient	Correct	Efficient
1	Yes	5	Yes	Yes	*	5	Yes	No	*	*	2	2
2	Yes	5	Yes	Yes	*	3	No	Yes	4	No	3	1
3	Yes	6	Yes	No	Yes	5	Yes	Yes	6	Yes	2	3
4	Yes	5	Yes	No	Yes	4	Yes	Yes	5	Yes	2	3
5	Yes	5	Yes	No	No	*	*	No	*	*	1	1
6	Yes	5	Yes	No	Yes	5	Yes	No	*	*	1	2
7	Yes	5	Yes	No	Yes	5	Yes	Yes	4	No	2	2
8	Yes	5	Yes	Yes	*	5	Yes	Yes	5	Yes	3	3
9	Yes	5	Yes	Yes	*	10	Yes	Yes	5	Yes	3	3
	Percentage Correct		100.0%	Percentage Correct			44.4%	Percentage Correct		66.7%		
	Percentage Efficient		100.0%	Percentage Correct (PRINT)			88.9%	Percentage Efficient		66.7%		
	Avg. LoC (Std. Dev.)		5.11 (0.33)	Percentage Efficient			87.5%	Avg. LoC (Std. Dev.)		4.83 (0.75)		
				Avg. LoC (Std. Dev.)			5.25 (2.05)					

(a) Exercise results for intermediate programmers using BASIC.

	Exercise 1			Exercise 2				Exercise 3			Total	
Subject	Correct	LoC	Efficient	Correct	Correct (Uart)	LoC	Efficient	Correct	LoC	Efficient	Correct	Efficient
1	Yes	8	Yes	No	No	*	*	Yes	10	No	2	1
2	Yes	9	Yes	No	No	*	*	Yes	12	No	2	1
3	Yes	8	Yes	No	No	*	*	Yes	16	Yes	2	2
4	Yes	9	Yes	No	No	*	*	No	*	*	1	1
5	Yes	8	Yes	No	No	*	*	Yes	9	No	2	1
6	Yes	8	Yes	No	No	*	*	No	*	*	1	1
7	Yes	6	Yes	No	No	*	*	No	*	*	1	1
8	No	*	*	No	No	*	*	Yes	10	Yes	1	1
	Percentage Correct		100.0%	Percentage Correct			0.0%	Percentage Correct		71.4%		
	Percentage Efficient		100.0%	Total Correct (PRINT)			0.0%	Percentage Efficient		50.0%		
	Avg. LoC (Std. Dev.)		8.00 (1.00)	Percentage Efficient			0.0%	Avg. LoC (Std. Dev.)		11.40 (2.79)		
				Avg. LoC (Std. Dev.)			*					

(b) Exercise results for intermediate programmers using TinyScript.

	Exercise 1			Exercise 2				Exercise 3			Total	
Subject	Correct	LoC	Efficient	Correct	Correct (PRINT)	LoC	Efficient	Correct	LoC	Efficient	Correct	Efficient
1	Yes	5	Yes	No	Yes	4	Yes	Yes	5	Yes	2	3
2	No	*	*	No	Yes	4	Yes	No	*	*	0	1
3	Yes	5	Yes	No	No	*	*	No	*	*	1	1
4	Yes	9	Yes	Yes	*	5	Yes	Yes	6	Yes	3	3
5	No	*	*	No	*	*	*	Yes	12	Yes	1	1
6	No	*	*	No	*	*	*	No	*	*	0	0
7	Yes	5	Yes	No	*	*	*	No	*	*	1	1
8	No	*	*	No	*	*	*	No	*	*	0	0
9	Yes	5	Yes	Yes	*	4	Yes	Yes	3	No	3	2
10	No	*	*	No	*	*	*	No	*	*	0	0
11	Yes	5	Yes	Yes	*	3	No	Yes	6	No	3	1
	Percentage Correct		54.5%	Percentage Correct			27.3%	Percentage Correct		45.5%		
	Percentage Efficient		100.0%	Percentage Correct (PRINT)			45.5%	Percentage Efficient		60.0%		
	Avg. LoC (Std. Dev.)		5.66 (1.63)	Percentage Efficient			80.0%	Avg. LoC (Std. Dev.)		6.40 (3.36)		
				Avg. LoC (Std. Dev.)			4.00 (0.71)					

(c) Exercise results for novice programmers using BASIC.

	Exercise 1			Exercise 2				Exercise 3			Total	
Subject	Correct	LoC	Efficient	Correct	Correct (Uart)	LoC	Efficient	Correct	LoC	Efficient	Correct	Efficient
1	No	*	*	No	No	*	*	No	*	*	0	0
2	No	*	*	No	No	*	*	No	*	*	0	0
3	No	*	*	No	No	*	*	Yes	15	No	1	0
4	No	*	*	No	No	*	*	No	*	*	0	0
5	No	*	*	No	No	*	*	No	*	*	0	0
6	No	*	*	No	No	*	*	No	*	*	0	0
7	No	*	*	No	No	*	*	No	*	*	0	0
8	No	*	*	No	No	*	*	No	*	*	0	0
9	No	*	*	No	No	*	*	Yes	8	Yes	1	1
10	No	*	*	No	No	*	*	No	*	*	0	0
11	No	*	*	No	No	*	*	No	*	*	0	0
12	No	*	*	No	No	*	*	No	*	*	0	0
	Percentage Correct		0.0%	Percentage Correct			0.0%	Percentage Correct		16.7%		
	Percentage Efficient		0.0%	Percentage Correct (PRINT)			0.0%	Percentage Efficient		50.0%		
	Avg. LoC (Std. Dev.)		*	Percentage Efficient			0.0%	Avg. LoC (Std. Dev.)		11.50 (4.95)		
				Avg. LoC (Std. Dev.)			*					

(d) Exercise results for novice programmers using TinyScript.

Figure 6. Exercise results for BASIC and TinyScript.

programmer-specified rate cannot be met.

To allow for event-driven computation, we extended the SLEEP statement to allow for mote wake-up based on an external interrupt, using hardware we previously developed [17]. The SLEEP statement can be modified using an optional keyword and the channel used to signal the interrupt. While waiting on an interrupt, the mote can remain in a low-power state, substantially reducing the power required to accurately detect transient events.

The study also prompted several smaller changes. In our original implementation, arguments to SENSE and LED functions specifying which sensor or LED to access were given as integer expressions to maximize flexibility. These arguments appeared to confuse several users of our language during our evaluation so these arguments were changed to keywords indicating the color of the LED actuated or the name of the sensor. Likewise, the SLEEP statement was modified to support durations in time units other than ms.

To support a more diverse set of applications, we added built-in function support to the BASIC interpreter, allowing for collections of domain-specific functions to be added to the interpreter at compile time. The functions are written in C, eliminating a potential energy and performance bottleneck for complex operations. This extensibility permits a decomposition of the problem where WSN or application development experts can write custom functions that can then be used by the domain experts in BASIC. Furthermore, it provides a path where commonly used functionality at the BASIC level can be hoisted into a function, including hardware, if it turns out to have performance or power problems.

Along with these changes, we are considering unifying the PRINT and SEND statements into a single communication abstraction, with the interpreter handling the choice of medium. Given our experience, such an abstraction would prove less confusing for inexperienced programmers. We plan on exploring this idea as we focus on salient communication abstractions novice WSN developers in future versions of our BASIC variant.

6.3 Experience with an Application

To further understand the utility of BASIC to domain experts, we conducted a second study in which domain experts implemented a structural monitoring application motivated by their research. We first solicited a sensor network application specification from a collaborator in structural monitoring. We then recruited students from our collaborator's lab who had not been previously involved in sensor network research to implement the task in BASIC. Although the study here is small scale and should therefore be taken anecdotally, the results do support the conclusions of the larger scale study of BASIC and show that domain experts can indeed use BASIC to quickly implement specifications given by a domain expert.

Our collaborator's description included two application tasks that are free of implementation-specific details. In the first task, the application periodically monitors an external string-displacement sensor connected to the sensor hardware's ADC. The application must collect 1,000 samples from the sensor at a rate of 1 kHz every 15 minutes to 2 hours. After each sampling period, the application must send the average of the collected samples along with a timestamp to the base station. Time synchronization between sensors is not required. The second task specified that the sensor be sampled at 500 Hz to 2.5 kHz for 3 to 10 seconds. Unlike the first, sampling occurs only when the output of an external sensor passes a given threshold. The sensor hardware detects when the external sensor passes this threshold via custom external event detection hardware previously developed by our group that generates an interrupt when the threshold is passed. The task requires that the application send all samples back to the base station.

We surveyed our collaborator's students' programming backgrounds and found that they had minimal programming background, at the level of "intermediate" in the results previously described in Section 6.1. One researcher reported experience with Matlab, which was learned in a classroom setting and used for course work and research. The other researcher reported experience with C/C++, Matlab, and Pascal also using the languages for course and project work. The two researchers reported maximum program sizes of 100 and 200 lines of code, respectively.

We conducted an experiment similar to our large-scale study. Each researcher was given 30 minutes to work through the BASIC tutorial, learn the language, and become familiar with the programming environment. We then presented the researcher with both of the programming tasks. The researcher was given 30 minutes to complete each task. When the researcher completed his task, we checked the program for correctness. If the program did not correctly implement the specification we explained that it did not (but not why), and asked the researcher to iterate in the remaining time.

For the first task, both researchers were able to succeed after one iteration. The initial errors included incorrect periodic behavior leading to only a single sample being taken, and an "off-by-one" array indexing error. The second iteration in both cases was correct and power-efficient. Both researchers were able to produce correct and efficient solutions to the second task in one iteration.

6.4 Power Consumption

To understand the overhead of using interpreted BASIC for sensor network applications we measured the energy required to execute typical sensor network tasks and provide an estimate of the typical overhead we would expect for programs written in BASIC. For interpreted BASIC, we find that while computationally intensive code sees a considerable drop in efficiency compared to C, a typical sensor network task involving data acquisition and communication suffers only a 1.5% increase in power consumption. Furthermore, compiled BASIC shows performance comparable to code written directly in C.

Experimental setup: In all our experiments, we compare an application written in BASIC to one written in C using Mantis OS for reading sensor values and performing communication. We compare the same BASIC code across our baseline interpreter as well as a modified interpreter that maintains a tokenized representation of the BASIC program. To evaluate compiled BASIC, as a proof-of-concept, we use an existing BASIC to C translator [29] to generate baseline C code to which we then add the appropriate calls to Man-

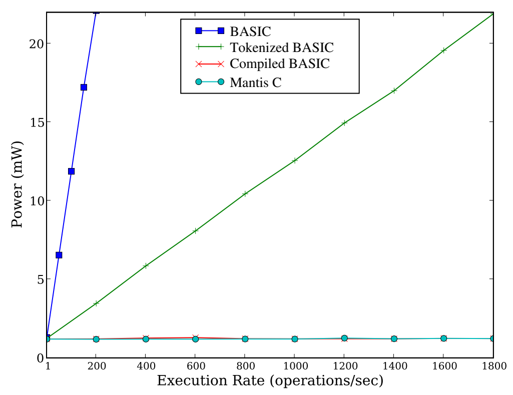


Figure 9. Power consumption versus execution rate.

tis. While we feel that the rapid development environment provided by an interpreted language aids novice programmers, we imagine that an application developer could deploy a compiled version of his or her code after it has been developed, debugged, and tested. In each power comparison, the code is functionally identical, with both the interpreter and both sets of C code relying on the same Mantis OS system calls.

To measure the worst-case overhead of the BASIC interpreter, we created a simple benchmark application that executes a loop summing all integer values within a range, sleeps for a fixed amount of time, and repeats. We use this application to estimate the power requirements of several different rates of execution between the two implementations. For the purposes of our comparison, we equate one iteration of the loop with one operation.

We also evaluate a typical sensor network use case by comparing the power requirements of a "sense and send" application. The goal of this application is to sense a value from the environment at the rate of 1 Hz and conditionally send a message to a base station if that value passes a given threshold. For this experiment, we set the threshold low enough such that the value is always transmitted.

We perform our measurements using a Crossbow MicaZ mote with an MTS300 sensor board. Power measurements are taken using a National Instruments 6036E data acquisition card connected to a PC running Windows XP. We measure the voltage across a 10 Ω resistor in series with the power supply to calculate the current.

Results: Figure 9 illustrates the computational and power overhead as we sweep the desired execution rate of our benchmark. For an iteration rate of one operation (iteration), the interpreter and native code solution have a difference of 0.1 mW. The non-optimized, non-tokenizing BASIC interpreter reaches a saturation point at approximately 200 operations per second at which point the interpreter cannot execute any faster. The tokenizing implementation experiences its saturation point at approximately 1,800 operations per second. At this execution rate, the interpreter uses about 18× more power than the native code solution. Note that the compiled version of BASIC allows for an execution rate roughly identical to that of C.

For the "sense and send" application, we measure an increase in power consumption of 1.5% for BASIC compared to native C, with the average power consumption of the BASIC application at 2.08 mW compared to the native C application at 2.05 mW. The tokenized version experiences a similar overhead of approximately 1.5%, while the compiled BASIC version has negligible overhead.

Our results indicate that a purely interpreted language like BASIC is acceptable for sensor network applications that are not compute-intensive, as is common. Tokenization increases the range of applications for which it is appropriate. Finally, compiled BASIC has computation performance and power characteristics that are virtually identical to C.

7 Conclusions

We have addressed the problem of making sensor networks easier to program by non-experts by exploring the use of an extended BASIC programming language in this domain. Our contributions include a user study evaluating how well novice (no programming experience) and intermediate (some programming experience) users can accomplish simple sensor network tasks in our version of BASIC and in TinyScript (an alternative also designed for inexperienced programmers). We also evaluate the power-consumption issues in interpreted languages like BASIC. Half of users with no previous programming experience of any kind were able to program simple network tasks using our BASIC. Our experimental results show that use of a BASIC interpreter has little impact on the power consumption of applications in which computational demands are low, while compiled BASIC behaves nearly identically to compiled C. We strongly encourage further evaluation of prospective languages for sensor networks via carefully designed user studies.

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