Trading off Complexity for Expressiveness in Programming Languages: Visions and Preliminary Experiences

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Abstract

When programming resource-scarce embedded smart devices, the designer often requires both the low-level system programming features of a language such as C and higher level capability typical of a language like Java. The choice of a particular language typically implies trade offs between conflicting design goals such as performance, costs, and overheads. The large variety of languages, virtual machines, and translators provides the designer with a dense trade off space, ranging from minimalistic to rich full-fledged approaches, but once a choice is made it is often difficult for the designer to revise it. In this work we propose a system of light-weighted and modular extensions as a method to flexibly reshape the target programming language as needed, adding only those application layer features that match the current design goals. In so doing complexity is made transparent, but not hidden: While the programmer can benefit of higher level constructs, the designer can deal with modular building blocks each characterized by a certain algorithmic complexity and therefore each accountable for a given share of the overhead. As a result the designer is given a finer control on the amount of resources that are consumed by the run-time executive of the chosen programming language.

1. Introduction

The July 2010 Tiobe Programming Community index [20], ranking programming languages according to their matching rate in several search engines, sets C as the second most popular programming language, barely 0.2% less than Java. C’s object-oriented counterpart C++ is third but quite further away (18.48% vs. 10.469%). Quite remarkably, C was still “programming language of the year” for Tiobe in 2008, exhibiting that is the highest rise in ratings in that year, as Java was in 2005. Both quite successful and wide-spread, C and Java represent two extremes of a spectrum of programming paradigms ranging from system-level to service-level development. Interestingly enough, in C complexity is mostly in the application layer, as its run-time executive is typically very small [13]; in Java, on the other hand, non-negligible complexity comes also with an often rich execution environment (EE). The latter comprises a virtual machine and advanced features such as autonomic garbage collection. The only way to trade off the EE complexity for specific services is then by switching to another EE.

Various EE’s are available, developed by third parties to match specific classes of target platforms. Fine-tuning the EE is also possible, e.g. in Eclipse; and of course it is also possible to go for a custom implementation. In general though the amount and the nature of the EE complexity is hidden to the programmer and the designer—after all, it is the very same nature of Java as a portable programming language that forbids to exploit such knowledge.

Though transparent, such hidden complexity is known to have an impact on several aspects, including overhead, real-timeliness, deterministic behavior, and security [7]. In particular, when a computer system’s expected activity is well defined and part of that system’s quality of service—as it is the case e.g. for real-
time embedded systems—then any task with unknown algorithmic complexity or exhibiting non-deterministic behavior might simply be unacceptable. As an example, a run-time component asynchronously recollecting unused memory, though very useful in itself, often results in asynchronous, unpredicted system activity affecting e.g. the processors and the memory system—including caches. Taking asynchronous tasks such as this into account would impact negatively on the analysis of worst-case execution times and consequently on costs as well.

In what follows we propose an alternative—in a sense, an opposite—direction: Instead of stripping functionality from Java to best match a given target platform, we chose to add functionality to C to compensate for lack of expressiveness and linguistic support. More specifically, in our approach, C with its minimalistic run-time executive becomes a foundation on top of which the designer is made able to easily lay a system of modular linguistic extensions. By doing so the above mentioned partitioning of complexity is not statically defined and unchangeable, but rather it becomes revisable under the control of the designer. Depending on the desired linguistic features and the overhead permitted by the target platform as well as by mission and cost constraints, our approach allows the programming language to be flexibly reshaped. This is because our approach employs well-defined “complexity containers”, each of which provides limited specific functions and each of which is characterized by well-defined complexity and overhead. Syntactic features and EE functions are weaved together under the control of the designer, resulting in bound and known complexity. A dynamic trade off between complexity and expressiveness can then be achieved and possibly revised in later development stages or when the code is reused on a different platform. In principle such combination of transparent functionality and translucent complexity should also reduce the hazards of unwary reuse of software modules [15].

The current version of our system is simply a proof-of-concepts; in particular the control of the augmentations is still manual, which makes our prototypical implementation far from being perfect. Assisted, automatic, or even intelligent assembling of our extensions is the matter of our current research.

The structure of this paper is as follows: In Sect. 2 we introduce a number of “basic components” respectively implementing extensions for context awareness, for autonomic data integrity, and for event management. In Sect. 3 we discuss how we built such components and how they may be dynamically recombined and thus give raise to specific language variants. Section 4 introduces a case study and some preliminary evaluation. Our conclusions are finally produced in Sect. 5.

2. Basic Components

This section introduces three basic components of our approach: Linguistic support to context awareness (Sect. 2.1), adaptive redundancy management (Sect. 2.2), and application-level management of cyclic events (Sect. 2.3). In all three cases the syntactical extension instruments the memory access operations on certain variables.

2.1. Context Awareness Component

Context awareness (CA) is defined here as the ability to expose certain properties and accordingly react to certain conditions in a transparent and intuitive way. Such properties may be endogenous or exogenous, and are called herein “the context”. Endogenous context describes properties of computer-specific processes: Structure and state of the software components, hardware properties, operating system state, policies supported by the EE—to name but a few examples. Exogenous context is properties regarding the processes occurring between a computer system and the physical world. More specifically, it is “any information that characterizes a situation related to the interaction of a computer system with humans, applications and the surrounding environment” [10].

In the rest of this section we focus on linguistic support to CA. This may take different forms depending on programming language design choices. Linguistic support to CA influences adaptability, which we define here as the ability to structure one’s function in accordance with a subset of the current endogenous and exogenous context conditions. Such subset represents a choice of context variables that are deemed as “sensible enough” to steer optimally the function of the system. Linguistic support to CA is the fundamental building block—at application layer—to build open and “self-*” systems, i.e. flexible, adaptive systems able to autonomically re-optimize themselves in the face of changes. Many high level programming languages support CA via e.g. computational reflection, composition filters, or aspects. Lacking such linguistic support it becomes more difficult and error-prone to design e.g. ambient-intelligent embedded devices. C has no built-in support for context awareness, which means that the designers requiring such service need to rely on “external” support, e.g. via middleware [12].
What we call the CA component of our architecture is a translator that filters an “augmented C” source code producing a standard C source code. Such output code makes use of a thread and the methods in an external library. The translator intercepts occurrences of specific variables that are interpreted as access points to actuators and sensors, in a way similar to the one described in [3]. Actuators are managed as overloaded assignment operators in C++: Writing to an actuator variable triggers a side-effect, defined as a user-selected method call. Sensors are managed through threads, which transparently update shared memory locations with the current value of a context property, e.g. the current state of a watchdog timer thread, reified as a value fitting in a C variable of some type. Available sensors reflect context information such as the amount of CPU currently being used or the state of external components, e.g. media players or watchdog timers. Guarded functions asynchronously evaluate expressions on the sensors and are executed when their guards become true.

The most notable difference between this approach and e.g. the one in [3] is that sensors and actuators can be represented here as dynamically growing arrays that are addressable by domain-specific indices. As an example, linkbeacons is an array of “objects” (actually, structures) that represent Medium Access Control layer properties of mobile ad-hoc network peers. A new object comes to life dynamically each time a new peer comes in proximity. When a peer node falls out of range, the corresponding object becomes “stale” until its node becomes reachable again. The linkbeacons array is addressed by strings representing the MAC address of peer nodes. Array linkbeacons reflects a number of properties, including the number of MAC beacons received by a peer node during the last “observation period” (defined in our experiments as sixty seconds) or the number of periods elapsed without receiving at least one beacon from a certain node.

Similarly, array linkrates returns Network layer properties of peers in proximity—in particular, it returns the estimated bandwidth between the current node and the addressed one.

The above mentioned arrays are currently being used in our research group to set up sort of cross-layer “switchboards” able to perform optimizations such as MAC-aware IP routing in mobile ad-hoc networks (see Fig. 1).

As can be seen in Fig. 2, the program used to steer this cross layer optimization is quite simple: Every new observation cycle, the program retrieves the MAC addresses of the peers in proximity via a simple function call (anext) and then requests to adjust the routing metric using the above mentioned arrays. The actual adjustments to the routing protocol are carried out through a Click [14] script.

2.2. Adaptive Redundancy Component

Another important service that is typically missing in conventional programming languages such as C is transparent data replication. As embedded systems are typically streamlined platforms in which resources are kept to a minimum in order to contain e.g. costs and power consumption, hardware support to memory error detection is often missing. When such embedded systems are mission critical and subjected to unbound levels of electromagnetic interference (EMI), it is not uncommon to suffer from transient failures. As an example, several Toyota models recently experienced unintended acceleration and brake problems. Despite Toyota’s official communications stating otherwise, many researchers and consultants are suggesting this to be just another case of EMI-triggered failures [19, 11, 21]. More definitive evidence exists that EMI produced by personal electronic devices does affect electronic controls in modern aircrafts [17], as it is the case for control apparatuses operating in proximity of electrical energy stations as well [8].

Whenever EMI causes unchecked memory corruption, a common strategy is to use redundant data structures [18]: Mission-critical data structures are then
"protected" by replication and voting and through re-doing [8]. Our adaptive redundancy component is just a filter that allows the user to tag certain variables as being "redundant". The filter transparently replicates those variables according to some policy (for instance, in separate "banks") and then catches memory accesses to those variables. Write accesses are multiplexed and store their "rvalues" [13] in each replica, while read accesses are demultiplexed via a majority voting scheme. Figure 3 summarizes this via a simple example.

In some cases, for instance when the application is cyclic and constantly re-executed as in [9], the behavior of the voting scheme can be monitored and provide an estimation of the probability of failure: As an example, if the errors induced by EMI are affecting a larger and larger amount of replicas, then this can be interpreted as a symptom for the imminent failure of the voting scheme due to the impossibility to achieve a majority. Detecting this and assessing the corresponding risk of voting failure allows the amount of replicas to be transparently and autonomically adjusted, e.g. as described in [2].

2.3. Cyclic Methods Component

As observed in [4], linguistic constructs such as repeat periodically, at time t send heartbeat, at time t check whether message m has arrived, or upon receive, are often used to produce pseudo-code for distributed protocols. The lack of those constructs in a language such as C led us in the past to implement a library of so-called "time-out objects". Such objects postpone an associated function call by a user-defined amount of time. In [4] we showed how this permits to implement the above constructs by converting time-based events into message arrivals or signal invocations. In the cited paper we also proposed some preliminary "syntactic sugar" to ease up the use of such objects in C.

Table 1. Example of usage of the TOM time-out management class. In 1. a time-out list pointer and two time-out objects are declared, together with two alarm functions. In 2. the time-out list and the time-outs are initialized. Insertion is carried out in 3. In 4., time-out t2 is disabled; its deadline is changed; t2 is restarted; and finally, time-out t1 is deleted.
Figure 3. A simple example of use of redundant variables. An “extended C” source code that accesses a redundant variable (left-hand image) and an excerpt from the translation in plain C (right-hand picture) are displayed.

```
#include <stdio.h>
int main(void)
{
    int a;
    redundant int myProtectedInteger;
    while (1)
    {
        sleep(1);
        myProtectedInteger = 1;
        a = myProtectedInteger;
    }
}

#include <stdio.h>
int main(void)
{
    int a;
    /* redundant */ int myProtectedInteger;
    // ...bookkeeping
    while (1)
    {
        sleep(1);
        redundantAssign_int(&myProtectedInteger); // multiplex
        a = redundantRead_int(&myProtectedInteger); // de-multiplex via voting
    }
}
// bookkeeping...
```

Table 2. The new syntax for the example of Table 1. Two simple constructs are introduced—bold typeface is used to highlight their occurrences in this example.

1. /* declarations */
   cyclic_t int PeriodicMethod1(TOM*);
   cyclic_t int PeriodicMethod2(TOM*);

2. /* definitions: unnecessary */

3. /* insertion */
   PeriodicMethod1.Cycle = DEADLINE1;
   PeriodicMethod2.Cycle = DEADLINE2;

4. /* control */
   PeriodicMethod2.Cycle = NEW_DEADLINE2;
   PeriodicMethod1.Cycle = 0;

3. Putting Things Together

In previous section we introduced a number of components each of which can be used to augment plain C with extra features. In the rest of this section we briefly describe the general design principles behind these components (Sect. 3.1) and then we introduce our current simplistic approach to combine them together (Sect. 3.2).

3.1. General Design Principles

The key principle of our approach is that of source-to-source program transformation through a set of independent and interchangeable extensions, each adopting a set of orthogonal (that is, non-overlapping) syntaxes. Extensions augment a same base language (in the case at hand, C) and in the face of local syntax errors, assume that the current line being parsed will be filtered by one of the following extensions. In other words, what would normally be regarded as severe errors is simply flushed onto the standard output stream in our current implementation. Obviously such strategy is far from ideal, as it shifts all possible syntax checks down to C compile time. A better strategy would be to let the system try different extensions on each input parsing block, or even better to have the system guess which extensions to apply based on the syntactic “signature” of each input fragment. We are currently designing yet another approach, in which “extension tags” are used to prefix the lines that are meant to be parsed by the corresponding extension. This im-

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1In some cases there might arise conflicts when the same C entity is referred in two or more extensions. A practical example of this is a same variable being addressed by two extension, as it is the case for watchdog in Sect. 4.
plies that in any given parsing unit only one extension will be allowed.

Our extensions are coded in C with Lex and YACC [16] and make use of some simple Bash shell scripts. Some extensions were originally developed on a Windows/Cygwin environment while more recent ones have been devised on Ubuntu Linux. All extensions run consistently on both environments.

Each of our extensions is uniquely identified at runtime by an extension identifier—a string in the form “cpm://e/v”, where e and v are two strings representing respectively the extension and its version number. “Cpm” stands for the way we currently refer to our system of extensions, that is “C++”.

3.2. Assembling Components

Our current implementation makes use of a simplistic strategy to assemble components, requiring the user to manually insert or remove the translators corresponding to each extension. In particular the user is responsible for choosing the order of application of the various extensions. Figure 4 shows the script that we use for this. A Unix pipeline is used to represent the assembling process. Components of this pipeline are in this case redundancy, which manages the extension described in Sect. 2.2, followed by refractive, which adds operator overloading capabilities to context variables. The last stage of the pipeline is in this case array, which produces the extension described in Sect. 2.1.

It is worth pointing out that each extension publishes its extension identifier by appending it to a context variable, a string called extensions_pipeline, e.g. “cpm://redundancy/1.1;cpm://refractive/0.5;cpm://array/0.5”. By inspecting this variable the executable is granted access to knowledge representing the algorithmic complexity and the features of its own execution environment.

Extensions refer to code and make use of threads defined in libraries and ancillary programs. Such ancillary code (and the ensuing complexity) is then selectively loaded on demand during the linking phase of the final compilation.

4. Some Preliminary Evaluation

In order to analyze the performance of our method we shall focus on a particular case study: The design of a software fault-tolerant watchdog timer (WDT). This particular choice stemmed from a number of reasons:

- First of all, WDT provides a well known and widespread dependable design pattern that is often used in either hardware or software in mission-critical embedded systems, as it provides a cost-effective method to detect performance failures [1].
- Secondly, a WDT is a real-time software. This means that it requires context awareness of time. This makes it suitable for being developed with the extension described in Sect. 2.1.
- Moreover, a WDT is a cyclic application. Linguistic constructs such as the one described in Sect. 2.3 allow a concise and lean implementation of cyclic behaviors.
- Furthermore, WDT is a mission-critical tool: A faulty or hacked WDT may cause a healthy watched component to be stopped; this in turn may severely impact on availability. Protecting a WDT’s control variables could help tolerating some faults and security leaks. The extension described in Sect. 2.2 may provide—to some extent—such protection.
- Finally, the choice of focusing on a WDT permits us to leverage from our past research: In [5] we introduced a domain-specific language that permits
to define WDTs in a few lines of code. This allows an easy comparison of the amount of the expressiveness of the two approaches.

A context variable called watchdog reflects the state of a WDT. States are reified as integers greater than −4. Negative values represent conditions, i.e. either of:

WD_STARTED, meaning that a WDT task is running and waiting for an activation message.

WD_ACTIVE, stating that WDT has been activated and now expects periodical heartbeats from a watched task.

WD_FIRED, that is, no heartbeat was received during the last cycle—the WDT “fired.”

WD_END, meaning that the WDT task has ended.

Positive values represent how many times the WDT reset its timer without “firing.”

That same variable, watchdog, is also an actuator, as it controls the operation of the WDT: Writing a value into it restarts a fired WDT.

Being so crucial to the performance of the WDT, we decided to protect watchdog by making it redundant. To do so we declared it as extern redundant_t int watchdog. Using the extern keyword was necessary in order to change the definition of watchdog into a declaration [13], as the context aware component defines watchdog already. In other words this is a practical example of two non-orthogonal extensions.

Figure 5 describes our illustrative implementation. The code uses all three extensions reported in Sect. 2. A WDT thread is transparently spawned. Such thread is monitored and controlled via variable watchdog. Redundant copies of this variable are used to mitigate the effect of transient faults or security leaks affecting memory. The code then uses our cyclic methods extension to call periodically a management function. Such function in turn makes use of two of our extensions—for instance, the WDT is restarted by writing a value into watchdog.

In order to evaluate the complexity introduced by our approach we divided complexity into an exogenous and an endogenous component, which we call respectively syntactical and semantic complexity.

Syntactical complexity is related to the expressiveness of the language available to the programmer. To roughly estimate this we assumed that a language’s expressiveness is inversely proportional to the lines of code required to program with it. If we restrict ourselves to the above discussed WDT we can observe how

```c
int main(int argc, char *argv[]) {
    RR_VARS
    /* this transparently launches the watchdog timer; */
    /* from now on, it can be controlled and monitored */
    /* via context variable 'watchdog' */
    /* RR_VAR_WATCHDOG */
    cyclic_t int wd_management(TOM);
    /* this declares a cyclic method for the */
    /* periodic management of the watchdog */
    extern redundant_t int watchdog;
    /* this requests to protect variable 'watchdog' */
    wd_management.Cycle = 2000;
    /* every 2 seconds, do execute wd_management */
    while (watchdog != WD_FIRED || wd_management.Cycle != 0)
        sleep(1);
    wd_management.Cycle = 0;
    return 0;
}

int wd_management(TOM *tom) {
    if (watchdog == WD_FIRED)
        /* restart WDT by setting 'watchdog' */
        watchdog = 0;
    else if (watchdog == WD_END)
        /* disable cyclic behavior */
        wd_management.Cycle = 0;
}
```

in this special case the programmer is required to produce an amount of lines of code notably lesser than what normally expected for a comparable C program. Such amount is slightly greater than in the case treated in [5], where a C implementation of a WDT is produced from a high level domain-specific language. It must be remarked though that the WDT produced by our former tool is much simpler than the one presented here—e.g. it is fault-intolerant and context agnostic.

Semantic complexity is the complexity necessary to express and make use of our extensions. A fair and objective estimation is more difficult in this case, as it would require us to compare different instances of our modular, loosely coupled extensions with as many monolithic implementations. We have not performed such a Sisyphean task; instead, we merely observe how our approach allows the designer to deal with a number of separated, limited problems instead of a single, larger problem. From the divide-and-conquer design principle we then conjecture a lesser complexity for our approach. Moreover, in our case the designer is aware and in full control of the amount and of the nature of the complexity he/she is adding to C. This in particular means that the programmer has fine-grained
knowledge and control over the overhead introduced by the EE as well as over its algorithmic complexity.

5. Conclusions

We have introduced an approach to gradually augment the features of a programming language by injecting a set of light-weighted extensions. Depending on the desired features and the overhead and behaviors permitted by the target platform and cost constraints, our approach allows the programming language to be flexibly reshaped. This is because our approach employs well-defined “complexity containers”, each of which grants limited specific functions and is characterized by well-defined complexity and overhead. By doing so, complexity is made transparent but it is not hidden: While the programmer can benefit of high level constructs, the designer and the deployer can deal with modular building blocks each characterized by a certain algorithmic complexity and therefore each accountable for a certain overhead. A mechanism allows each building block to be identified, thus avoiding mismatches between expected and provided features. At the same time, this provides the designer with finer control over the amount of resources required by the run-time executive of the resulting language.

Our current implementation is merely a proof of concepts; as such it is rather limited and in particular sacrifices elegance and efficiency to fast prototyping. Future work will focus on improving these aspects and especially on schemes to automatically assemble required extensions and perform more strict analyses of syntax errors, e.g. by labeling parsing lines with “extension tags”. Proper GNU build system scripts will be written to automate extension assembling and final code compilation. Other work will include designing a public API for third parties to develop their own extensions. New extensions shall be designed, e.g. one addressing parallel programming through the LINDA primitives and inspired by our previous work [6], and a second one to manage “service groups”, i.e. redundant groups of task replicas. The latter could be used to realize constructs such as the redundant watchdog of [5].

Acknowledgments

We would like to thank Nicolas Letor for designing the network components of our switchboard application and for the ideas we exchanged while designing our context aware extension.

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