Asynchronous Programming in a Prioritized Form

Mohamed A. El-Zawawy\textsuperscript{1,2}
\textsuperscript{1}College of Computer and Information Sciences
Al Imam Mohammad Ibn Saud Islamic University
Riyadh, Kingdom of Saudi Arabia
\textsuperscript{2}Department of Mathematics
Faculty of Science
Cairo University
Giza 12613, Egypt
maelzawawy@cu.edu.eg

Abstract: Asynchronous programming has appeared as a programming style that overcomes undesired properties of concurrent programming. Typically in asynchronous models of programming, methods are posted into a post list for later execution. The order of method executions is serial, but nondeterministic. This paper presents a new and simple, yet powerful, model for asynchronous programming. The proposed model consists of two components: a context-free grammar and an operational semantics. The model is supported by the ability to express important applications. An advantage of our model over related work is that the model simplifies the way posted methods are assigned priorities. Another advantage is that the operational semantics uses the simple concept of singly linked list to simulate the prioritized process of methods posting and execution. The simplicity and expressiveness make it relatively easy for analysis algorithms to disclose the otherwise un-captured programming bugs in asynchronous programs.

Key–Words: Prioritized posting, asynchronous programming, operational semantics, context-free grammar, concurrent programming.

1 Introduction

All contemporary appliances (mobile, desktop, or web applications) require high responsiveness which is conveniently provided by asynchronous programming. Hence application program interfaces (APIs) enabling asynchronous, non-blocking tasks, such as web access or file operations) are accommodated in dominant programming languages. APIs provide asynchronous programming but mostly in a hard way. For example consider the following situation. A unique user interface (UI) task thread is typically used to design and implement user interfaces. Hence events on that thread simulate tasks that change the UI state. Therefore when the UI cannot be redrawn or respond, it get freezeed. This makes it sensible, in order to keep the application responding continuously to UI tasks, to run blocking I/O commands and long-lasting CPU-bound asynchronously.

Asynchronous programming has multi-threaded roots. This is so as APIs have been implemented using multi-threaded programs with shared-memory. Software threads execution is not affected by the number of processors in the system. This is justified by the fact that the threads are executed as recursive sequential softwares running concurrently with interleaved write and reads commands. The many possible interleavings in this case cause the complexity of models of concurrent programming \cite{8}. In a complex process, atomic locking commands can be added for prevention and prediction of bad thread interleavings. The non-deterministic style of interleaving occurrence creates rarely appearing programming-errors which are typically very hard to simulate and fix. This difficulty lead researchers to design multi-threaded programs (of APIs) in the framework of asynchronous programming models \cite{6,7}.

The relative simplicity of asynchronous programming makes it a convenient choice to implement APIs or reactive systems. This is proved by recent years intense use of asynchronous programming by servers, desktop applications, and embedded systems. The idea of asynchronous programming is to divide cumulative program executions into tasks that are briefly-running. Moreover accessing the shared memory, each task is executed as a recursive sequential software that specifies (posts) new methods to be executed later.
Many attempts were made to present formal asynchronous programming models. However few attempts [5] were made to express and formalize the fact that posted tasks in asynchronous programs may well have different execution priorities. A big disadvantage of existing work [5] that considers execution priorities is the complexity of the models hosting such priorities. For example the work in [5] considers the execution priorities using several task-buffers which makes the solution a bit involved.

This paper presents a simple, yet powerful, model for asynchronous programming with priorities for task posting. We call the proposed model \texttt{Asynch}_P. The paper also presents a novel and robust operational semantics for the constructs of \texttt{Asynch}_P. A simple singly linked list of prioritized posted tasks is used to precisely capture the posting process. Our proposed asynchronous model is to simplify analyzing asynchronous programs [4].

Motivating Example

A motivating example of designing our model comes form the way hardware interactions take place in operating systems (more specifically in Windows) kernels. Concepts of prioritized interrupt sets are used to simulate these hardware interactions in an asynchronous style. For such applications a simple, yet powerful and mathematically well founded, model for prioritized asynchronous programming is required.

Contribution

The contributions of this paper are:

- A prioritized asynchronous programming model; \texttt{Asynch}_P.

- A novel operational semantics for \texttt{Asynch}_P programs.

Organization

The rest of the paper is organized as follows. Section 2 presents the proposed prioritized asynchronous programming model – \texttt{Asynch}_P. The semantics of prioritized asynchronous programming model; \texttt{Asynch}_P is shown in Section 3 which is followed by Section 4 that reviews related work and presents directions for future work. The last section (Section 5) of the paper concludes it.

2 Prioritized Asynchronous Programming Model

This section presents our model, \texttt{Asynch}_P, for prioritized asynchronous programming. In \texttt{Asynch}_P, each posted method has an execution priority. An asynchronous program execution is typically divided into quick-running methods (tasks). Tasks of higher priority get executed first and task of equal priorities are executed using the first come first served strategy. Asynchronous programming has an important application in reactive systems where a single task must not be allowed to run too long and to prevent executing other (potentially) highly prioritized tasks.

Figure 1 presents the simple and powerful model \texttt{Asynch}_P for prioritized asynchronous programming. Considering single local and global variables and using free syntax of expressions does not cause any generality lose. However each expression is built using the global variable of the program and the local variable of the active method. A \texttt{Asynch}_P program \texttt{P} consists of a single global variable \texttt{g} and a sequence of methods denoted \texttt{M}_1, \ldots, \texttt{M}_n. The \texttt{Provided(e)} statement continues executing the program provided that the expression \texttt{e} evaluates to a non-zero value.

Each method \texttt{M} is expressed as a structure \texttt{meth}(\texttt{m}, \texttt{l}, \texttt{S}) of a method name, a single local variable \texttt{l}, and a top-level statement \texttt{S}. The sets of all program methods and statements are denoted by \texttt{Meths} and \texttt{Stmts}, respectively. Intuitively, the asynchronous call is modeled by the statement \texttt{Synch}(\texttt{m(e)}, \texttt{p}) where:

- the called method name is \texttt{m},
- the calling parameter is the expression \texttt{e}, and
- the execution priority of this call is \texttt{p}.

We assume three levels of execution priorities; \{high(1), medium(2), low(3)\}.

3 Mathematical Framework for \texttt{Asynch}_P

This section presents a novel operational semantics for asynchronous programs built using \texttt{Asynch}_P. Our semantics is based on a singly liked-list (which we call \texttt{Asynchronous Linked List (ALL)}) to host the posted methods. \texttt{ALL} is divided into three regions using pointers. The first, the middle, and last regions of \texttt{ALL} host posted methods that have high, medium, and low execution priorities, respectively.

Definition [1] introduces formally the concept of (Asynchronous Node (AN)) to be used to build \texttt{ALL}. 

\begin{align*}
\text{Stmts} &= \{\text{meth}(\texttt{m}, \texttt{l}, \texttt{S}) \mid \texttt{S} \in \text{Stmts} \}\; (1) \\
\text{Meths} &= \{\text{meth}(\texttt{m}, \texttt{l}, \texttt{S}) \mid \texttt{l} \in \text{LocV} \}\; (2) \\
\text{ALL} &= \{\text{meth}(\texttt{m}, \texttt{l}, \texttt{S}) \mid \texttt{m} \in \text{Meths} \}\; (3)
\end{align*}
An asynchronous node (AN), \( n \), is a single linked list node whose data contents are two locations containing:

- \( x_1 \): a method name, and
- \( x_2 \): a parameter expression.

For a method call \( m(e) \) in a \( \text{Asynch}_P \) program, we let \( \text{Node}(m(e)) \) denotes the asynchronous node whose locations \( x_1 \) and \( x_2 \) contain \( m \) and \( e \), respectively. The set of all asynchronous nodes is denoted by \( \text{Nodes}_A \).

Definition 2 introduces formally the concept ofAsynchronous Linked List (ALL) that is to be used to accurately capturing the semantics of the constructs of the proposed asynchronous model.

An asynchronous linked list (ALL),

\[ \text{li} = < f, c, e_h, e_m >, \quad (1) \]

is a singly linked list whose nodes are asynchronous nodes (in \( \text{Nodes}_A \)) such that:

- \( f \) is a pointer to the first node of the list,
- \( c \) is a pointer to the current node, and
- \( e_h, e_m \) are pointers to the last node in the list hosting a method of high and medium priorities, respectively.

The set of all asynchronous linked lists is denoted by \( \text{Lists}_A \).

Whenever a method gets posted, an asynchronous node is created and inserted into an asynchronous list. If the posted method is of priority \( h \) or \( m \), the created node gets inserted after the nodes pointed to by \( e_h \) or \( e_m \), respectively. If the posted method is of priority \( l \), the created node gets inserted at the end of the list. Whenever a posted method is to be executed, the method corresponding to the head of an asynchronous node is executed and that head gets removed from the list. These two operations are assumed to be carried out by the functions defined in Definition 3.

Definition 3 Let \( \text{li} = < f, c, e_h, e_m > \) be a asynchronous linked list (in \( \text{Lists}_A \)). We let

- \( \text{add}_A : \text{Nodes}_A \times P \times \text{Lists}_A \to \text{Lists}_A \) denotes a map that adds a given node \( n \) of a given priority \( p \) after the node pointed to be \( \text{li} \). \( e_p \) in a given list \( \text{li} \).
- \( \text{remove}_A : \text{Lists}_A \to \text{Nodes}_A \times \text{Lists}_A \) denotes a map that removes the first node of a given list \( \text{li} \) and return the removed node and the resulting linked list.

Definition 4 introduces the states of our proposed operational semantics.

Let \( \text{program}(g, M_1, \ldots, M_n) \), where \( M_i = \text{meth}(m_i, l_i, S_i) \), be a program in \( \text{Asynch}_P \). An asynchronous program state (APS) is a triple \((s, \text{li}, \text{sk})\), where:

- \( s \) is a partial map from \( G \cup (M \times L) \) to \( \text{Val} \).
- \( \text{li} \) is an asynchronous linked list.
- \( \text{sk} \) is stack of method names.

We let \( M_i.l \) and \( M_i.l \) denote \( l_i \) and \( S_i \), respectively.

Each semantic state is a triple of a partial map captures the contents of global and local variables, an asynchronous linked list, and a stack of method names.

\[ \text{Note that } p \in \{h, m, l\}. \text{ If } p = l, e_i \text{ is the last node in the list.} \]
The rule \((\text{prog}^*)\) first runs the statements of all methods of the program being executed then runs all statements of the methods that is posted. The posted statements are executed via the rules \((\Rightarrow_1^*)\) and \((\Rightarrow_2^*)\).

## 4 Related and Future Work

Parallel, distributed, reactive, and concurrent programming have been attracting much researcher activities. The asynchronous programming methodologies include:

- multi-threaded light-weight orchestration programming \([19]\),
- thread Join-based allocation,
- typed synchronous programming languages \([20]\),
- functional sensible programming,

Figures 2 and 3 present the transition rules of the proposed operational semantics. Some comments on the rules are in order. The rule \(\text{synch}^a\) creates an asynchronous node corresponding to the method \(m\) and the parameter \(e\). Using the map \(\text{add}_A\), the node then is added to the asynchronous list \(li\) to get the new list \(li'\). The rule \(\text{return}^a\), pops an element from the method stack as the return statement means that the top element of the stack is executed. The rule \(\text{run}^a\) first peeks the first element of the stack to get the local variable \(l\) of the currently active method. This local variable is then used together with the global variable to evaluate the expression \(e\). The resulting value is used to modify the local variable of the method \((m)\) that is to be executed. Then \(m\) is pushed into the stack and the statement of \(m\) is executed.

![Figure 2: Transition rules for statements.](image-url)
Event-based techniques for programming have been using continuations which are delimited monadic [17, 18]. Fork-join, task, async, and event functions appear not to rely on a specific language design. There is a big research debate about the relationship between threads and events in systems research [16].

In an asynchronous program, executions containing context switches bounded by a user-specified limit are explored by context-bounded verification [14, 15]. This context-bounding idea is not reasonable for programs with big number of events. Several treatments for this problem have been proposed for this problem. Without losing decidability, [13] proposed a context-minimizing technique permitting unbounded context switches. For asynchronous concurrent programs, in [12], the round-robin technique for scheduling is used to enable unbounded context switches.

Sequential techniques are also used to analyze asynchronous programs. In [14], a source-to-source technique building sequential programs from multi-threaded programs was proposed via under approximating the possible set of executions of the input program. A novel source-to-source transformation providing for any context-bound, a context-bounded under approximation was presented in [11]. A main issue of the work in [11] is that the resulting sequential program may host main states unreachable in the given asynchronous program. Other techniques like [10] treat this problem by repeatedly running the code to the control points where used-defined valued are needed. The work in [9] compares the techniques of asynchronous programs verifications that use verification-condition-checking against that use model-checking. One major results of this work is that eager approaches outperforms lazy ones. The work in [8] uses the construction using a bound on the task number, to reduce asynchronous programs into sequential programs via priority-preemptive schedulers.

The work presented in this paper is close to sequentialization [14]; the concept describing compositional reductions to get sequential programs from concurrent ones. Although sequentialization started by checking multi-threaded programs with one context-switch, it was developed later to treat a user-specified number of context-switches. These switches occur among statically-specified group of threads running using RR order [11]. In [2], a technique for treating context switches among an unspecified number of dynamically-created tasks was presented. This technique (in [2]) hence explicitly treats event-oriented asynchronous programs.

For future work, it is interesting to devise static analyses for asynchronous programs using the model AsyncTP [11]. Initial experiments show that our proposed model is expected to support devising robust and powerful analysis techniques. An examples of targeted analyses is dead-posting elimination which aims at removing the unnecessary posting statements from asynchronous programs.

5 Conclusion

Main reason to use asynchronous programming is to overcome some problems of concurrent programming. The main idea of asynchronous programming is to post methods into a post list for latter execution. The order of executing these methods is nondeterministically serial.

A new and simple, yet powerful, model for asynchronous programming was presented in this paper. More precisely, the paper proposed a context-free grammar and an operational semantics for asynchronous programming. One important aspect of the proposed model is supporting posting methods with
execution priorities.

References:

[1] El-Zawawy, M.A.: Detection of probabilistic dangling references in multi-core programs using proof-supported tools. In: Murgante, B., Misra, S., Carlini, M., Torre, C.M., Nguyen, H.-Q., Taniar, D., Apduhan, B.O., Gervasi, O. (eds.) ICCSA 2013, Part V. LNCS, vol. 7975, Springer, Heidelberg (2013), pp. 516–530.

[2] M. Emmi, S. Qadeer, and Z. Rakamaric. Delay-bounded scheduling. In POPL 11: Proc. 38th ACM SIGPLAN-SIGACT Symposium on Principles of Programming Languages, ACM, 2011, pp. 411–422.

[3] N. Kidd, S. Jagannathan, and J. Vitek. One stack to run them all: Reducing concurrent analysis to sequential analysis under priority scheduling. In SPIN 10: Proc. 17th International Workshop on Model Checking Software, volume 6349 of LNCS, Springer, 2010, pp. 245–261.

[4] M. F. Atig, A. Bouajjani, and T. Touili. Analyzing asynchronous programs with preemption. In FSTTCS 08: Proc. IARCS Annual Conference on Foundations of Software Technology and Theoretical Computer Science, volume 2 of LIPIcs, Schloss Dagstuhl - Leibniz-Zentrum fuer Informatik, 2008, pp. 37–48.

[5] Michael Emmi, Akash Lal, Shaz Qadeer: Asynchronous programs with prioritized task-buffers. SIGSOFT FSE 2012, 48.

[6] K. Sen and M. Viswanathan. Model checking multithreaded programs with asynchronous atomic methods. In CAV 06: Proc. 18th International Conference on Computer Aided Verification, volume 4144 of LNCS, Springer, 2006, pp. 300–314.

[7] R. Jhala and R. Majumdar. Interprocedural analysis of asynchronous programs. In POPL 07: Proc. 34th ACM SIGPLAN-SIGACT Symposium on Principles of Programming Languages, ACM, 2007, pp. 339–350.

[8] N. Kidd, S. Jagannathan, and J. Vitek. One stack to run them all: Reducing concurrent analysis to sequential analysis under priority scheduling. In SPIN ’10: Proc. 17th International Workshop on Model Checking Software, volume 6349 of LNCS, Springer, 2010, pp. 245–261.

[9] N. Ghafari, A. J. Hu, and Z. Rakamaric. Contextbounded translations for concurrent software: An empirical evaluation. In SPIN ’10: Proc. 17th International Workshop on Model Checking Software, volume 6349 of LNCS, Springer, 2010, pp. 227–244.

[10] S. La Torre, P. Madhusudan, and G. Parlato. Reducing context-bounded concurrent reachability to sequential reachability. In CAV ’09: Proc. 21st International Conference on Computer Aided Verification, volume 5643 of LNCS, Springer, 2009, pp. 477–492.

[11] A. Lal and T. W. Reps. Reducing concurrent analysis under a context bound to sequential analysis. Formal Methods in System Design, 35(1), 2009, pp. 73–97.

[12] S. La Torre, P. Madhusudan, and G. Parlato. Model checking parameterized concurrent programs using linear interfaces. In CAV ’10: Proc. 22nd International Conference on Computer Aided Verification, volume 6174 of LNCS, Springer, 2010, pp. 629–644.

[13] M. F. Atig, A. Bouajjani, and S. Qadeer. Context bounded analysis for concurrent programs with dynamic creation of threads. In TACAS ’09: Proc. 15th International Conference on Tools and Algorithms for the Construction and Analysis of Systems, volume 5505 of LNCS, Springer, 2009, pp. 107–123.

[14] S. Qadeer and D. Wu. KISS: Keep it simple and sequential. In PLDI ’04: Proc. ACM SIGPLAN Conference on Programming Language Design and Implementation, ACM, 2004, pp. 14–24.

[15] S. Qadeer and J. Rehof. Context-bounded model checking of concurrent software. In TACAS ’05: Proc. 11th International Conference on Tools and Algorithms for the Construction and Analysis of Systems, volume 3440 of LNCS, Springer, 2005, pp 93–107.

[16] G. Kerneis, J. Chroboczek, Continuation-Passing C, compiling threads to events through continuations, Higher-Order and Symbolic Computation (LISP), 24(3), 2011, pp. 239–279.

[17] A. Holzer, L. Ziarek, K. Jayaram, P. Eugster, Putting events in context: aspects for event-based distributed programming, AOSD, 2011, pp. 241–252.

[18] L. Vaseux, F. Otero, T. Castle, C. Johnson, Event-based graphical monitoring in the EpochX genetic programming framework, GECCO (Companion), 2013, pp. 1309–1316.

[19] R. Ranjan, B. Benatallah, Programming Cloud Resource Orchestration Framework: Operations and Research Challenges, CoRR abs/1204.2204, 2012.

[20] J. Aguado, M. Mendler, R. Hanxleden, I. Fuhrmann, Grounding Synchronous Deterministic Concurrency in Sequential Programming, ESOP, 2014, pp. 229–248.
[21] G. Gori, E. Johnsen, R. Schlatte, V. Stolz, Erlang-Style Error Recovery for Concurrent Objects with Cooperative Scheduling. *ISOFA*, 2014, pp. 5–21.

[22] J. Nelson, Co-ops: concurrent algorithmic skeletons for Erlang. *Erlang Workshop*, 2012, pp. 61–62.