University of Glasgow | School of Computing Science

Session types in the wild

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Contents

1 Introduction

Nowadays, distributed systems are ubiquitous and communication is an important feature and reason for its success. Communication-centred programming has proven to be one of the most successful attempts to replace shared memory for building concurrent, distributed systems. Communication is easier to reason about and scales well as opposed to shared memory, making it a more suitable approach for systems where scalability is a must, as in the case of multi-core programming, service-oriented applications or cloud computing[1].

Communication is usually standardised via protocols that specify the possible interactions between the communicating parties in a specific order. Mainstream programming languages fail to adequately support the development of communication-centred software. Thus, implementations of communication behaviours are based on informal protocol specification and thus informal verification. As a result they are prone to errors such as communication mismatch, when the message sent by one party is not expected by the other party, or deadlock, when two parties are waiting for a message from each other causing the system to block[1].

To allow formal protocol specification within the programming language session types have been devised. Session types describe communication by specifying the type and direction of messages exchanged between two parties[6]. Programmers can express a protocol specification as a session type, which can guarantee, within the scope where the session type applies, that communications will always match and the system will never deadlock. The main goal of the ABCD project[1] is to improve the practice of software development for concurrent and distributed systems through the use of session types. This is to be accomplished through built-in language support for protocol codification in existing languages such as Java or Python, in new languages such as Links[1], inter-language interoperability via session types, and through adapting interactive development environments and modelling techniques to support session types. Logical and automata foundations of session types will be further developed to express a wider class of behaviour and, as need arises, to support the former. Empirical studies to assess methodologies and tools are to be carried out, with results being used to improve language and tool design and implementation.

1.1 Research Outline

This PhD will attempt to answer the following questions considering both the theoretical and practical aspects of session types.

- How can programmers use session types in meaningful ways?
  - What are the strengths and weaknesses of the options for programming with session types?
  - Can programmers reason effectively about communication using session types?
  - Does the method of expressing session types influence the programmers' the ability to reason effectively about the system?

  These questions will be explored trough user studies, the first of which is outlined below in 3.4.

- What are the theoretical and practical challenges to expressing real life protocols with session types? And how can these be overcome?

1.2 Thesis Statement

Session types are a useful addition to the syntax and semantics of modern languages. Programming with session types and the constraints that this comes with i.e. linearity can be understood and used by real world programmers. Moreover session types can help programmers understand the problem they are tying to solve with more ease and structure their code better. Session typed languages provide useful additional safeguards and diagnostic information that lead to a system with the expected behaviour with less effort.

2 Literature review

2.1 Session types, a short history

Session types have been introduced by Honda[20], and further extended by Takeuchi et al.[33], Honda et al.[21], and others.

Session types are a way of modelling communication between different entities and enforcing the order of communication, as well as the types of the messages that may be sent. A session type describes the types of individual messages and the state transitions of the protocol i.e. the allowed sequences of messages. Each end of a communication channel is associated with a session type, which is the dual of the other, meaning that if the session type for one process prescribes that it may only send a string, then the other party may only receive an string. Type-checking may be used to verify processes compliance to the session type system and establish properties such as deadlock and race freedom, or session fidelity between two parties.

Session types have and continue to be the subject of a wide body of work aimed at extending their theoretical foundations as well as developing new tools and techniques. For example, session types have been augmented with subtyping polymorphism to enable protocols to describe richer behaviours[16]. They have been extended to ensure the progress property and deadlock freedom [11]. Session types have also been extended to multiparty session types to support communication instances with more than two participants while still guaranteeing the absence of deadlock[22]. In other work [8], global session types have been used to detect choreographies that can be realized in the context of web services.

Session types have been successfully applied in functional programming languages [34, 4], object-oriented languages like Java [23, 17], low-level programming languages like C in [29], dynamically-typed languages like Python[28] or Erlang [27], or in the operating systems context with the Sing# language [12].

From the literature surveyed, two main areas of interest will be presented bellow, namely typestate and language usability and evaluation.

2.2 Typestate

Typestate is a refinement of the concept of a type in programming. A typestate defines the valid sequence of operations that can be performed on an instance of a certain type by associating state information with variables of that type. This state information can then be used at compile-time to determine the operations that can be invoked with valid results on an instance of a type. A typical example is that of a file, which can be read or written only after being open, and never after being closed. In most cases such constraints on the sequences of method calls are at best informally documented through method descriptions or comments. However in this form, the information cannot be used by the compiler to detect any violations.

Since typestate has been introduced in[31], there have been many efforts to add it to practical programming languages. In [10], the concept of typestate, originally introduced for imperative programs, was extended for the object-oriented paradigm, resulting in the Fugue system. Sing# [13] is an extension of C# which incorporates typestate-like contracts, to specify protocols. Sing# has been successfully used to implement Singularity, a message-passing based operating system used for research at Microsoft. A core calculus for *Sing#* has been introduced in Bono et al. [7] proved type safe.

Plural[6] is another noteworthy example. Based on Java, it has been used to study access control systems[5] and transactional memory[3], and to evaluate the effectiveness of typestate in Java APIs[6]. However, Plural's use of annotations to define typestates is not ideal, while annotations are convenient for attaching extra information that can be consumed by tools, it makes expressing more complex concepts difficult and can be a burden on the programmer. Plural provides static analysis, and does not alter the runtime representation of classes in any way. Consequently, dynamic checking might still be needed if the system will interact with components that are not trusted.

To date, the only comprehensive attempt at designing and implementing a full general pur- pose programming language from scratch which draws together the state of the art in the theory of typestate is the Plaid language [2, 141].

Plaid is a gradually typed [136, 137, 153] language, meaning that it is a dynamically typed language in which type requirements and guarantees can be specified and statically checked in a selective manner. This technique largely mitigates the cost to the programmer of large type annotations, as they are optional, with the trade-off that method availability must be checked on every method call which adds a significant runtime overhead. Plaid defines objects as a collection of related state declarations that define a hierarchical, parallel finite state machine. The state hierarchy is defined explicitly by declaring one state to be a sub-state of another; Listing 2.3 demonstrates this through the definition of an option type. Explicitly defined constructors are not necessary in Plaid instead, a default con- structor exists for each defined state that initialises all fields and methods that are defined with an initial value. Other fields can be initialised through the use of an associated code block as shown on Line 12 of Listing 2.3, where an object is instantiated in state Some with the value field initialised to the result of f(value). Plaid does not support parametric polymorphism for states, meaning that we cannot annotate the Option type with a type parameter and insist that the field value be of this type statically. As the language is dynamically typed this is of little practical consequence, but is a major limitation for the static analysis. Plaid obviates the need for dynamic state test methods by allowing pattern matching on an objects type, as shown on Line 22. The hasValue method is defined for option values, but exists purely for programmer convenience rather than as a necessary part of the objects protocol.

Aldrich et al. [2, 32] have proposed *typestate-oriented programming* that goes one step further and incorporates typestates as native feature of the programming language, and encourages developers to design objects around their protocol.

Languages supporting TSOP provide explicit constructs for defining state-dependent object interfaces and implementa- tions, for changing and possibly querying at runtime an ob- jects typestate, and for annotating the signature of methods so as to describe their effect on the state of an object [1].

implemented in the Plaid language. The aim is to integrate typestate into a language design from the beginning. Instead of class definitions, a program consists of state definitions containing methods that cause transitions to other states. Transitions are specified in a similar way to Plural's pre- and post-conditions. Like classes, states are organised into an inheritance hierarchy. The most recent work [15, 35] uses gradual typing to integrate static and dynamic typestate checking. We focus on the object-oriented paradigm in order to be able to apply our results to Java.

Typestate systems must control aliasing, otherwise method calls via aliases can cause inconsistent state changes. We have not yet investigated alias control systems that are more sophisticated than linear typing. There is a large literature, which includes the "adoption and focus" approach of Vault and Fugue, the permission-based approaches of Plural and Plaid, and an expressive fine-grained system by Militão et al. [26]. We expect that many of these systems can be applied to Mungo. However, linear typing has not been a limiting factor for the applications described in the present pape

Gay et al. [18] proposed the integration of session types and object-oriented programming through the discipline of typestate[31], in which methods are constrained to be called only in a particular order. They consider a session type as being a special case of typestate, constraining the use of send and receive methods, and introduce a session-inspired notation for specifying method sequences.

In contrast Mungo follows Gay et al. which is inspired by session types; the possible sequences of method calls are explicitly defined, rather than being consequences of pre- and post-conditions. Like Plural, a typestate in Mungo can depend on the return value of a method call.

For the Mungo tool[**?**], the approach of [18] is followed, to formalise a typestate inference system for a core object-oriented language and prove its correctness. Mungo is implemented as a front-end typechecking tool for a subset of Java. Inference removes the need for typestate annotations on parameters and return types as in the system by Gay et al [18].

Mungo does not allow aliasing of objects that have a typestate protocol, to avoid the possibility of conflicting state changes through different aliases. It should be possible to orthogonally add more flexible alias control systems; there is a large literature to draw on.On the other hand, aliasing control that takes into account the particularities of session-based concurrency is a subject for future research.

The basic difference between Mungo and other typestate approaches is the Java-like syntax for describing state machine protocols, instead of associating pre- and post-conditions with methods. The motivation for developing such a typestate syntax is the ability to globally describe object behaviour and subsequently the general integration of session behaviour in objects.

2.3 Language usability and evaluation

Programming languages exist to enable programmers to develop software effectively. But how efficiently programmers can write software depends on the usability of the languages and tools that they develop with. The aim of this workshop is to discuss methods, metrics and techniques for evaluating the usability of languages and language tools. The supposed benefits of such languages and tools cover a large space, including making programs easier to read, write, and maintain; allowing programmers to write more flexible and powerful programs; and restricting programs to make them more safe and secure.

PLATEAU gathers the intersection of researchers in the programming language, programming tool, and human-computer interaction communities to share their research and discuss the future of evaluation and usability of programming languages and tools.

Some particular areas of interest are: A user study for comparing the programming efficiency of modifying executable multimodal interaction descriptions. A domain-specific language versus equivalent event-callback code.

Author[s]: Fredy Cuenca, Jan Van den Bergh, Kris Luyten, Karin Coninx Summary: This paper describes an empirical user study intended to compare the programming efficiency of our proposed domain-specific language(Hasselt) versus a mainstream event language(C#) when it comes to modifying multimodal interactions(multiple input modalities).

By concerted use of observations, interviews, and standardized questionnaires, they measured the completion rates, completion time, code testing effort, and perceived difficulty of the programming tasks along with the perceived usability and perceived learnability of the tool supporting the proposed language(Hasselt UIMS- User Interface Management Systems). propose some guidelines for designing comparative user studies of programming languages. Problem Solved: User Interface Management Systems = tools aiming at simplifying and speeding up the prototyping of multimodal systems

Problems with the adoption of UIMSs and domain-specific languages in the past.

At runtime, the UIMS responds to its end users by launching the methods of an externally developed application. At design time, the programmer has already specified, through a domain-specific language, the methods that have to be launched for each set of user inputs.

Evaluate UIMSs in user studies Approach: concerted use of observations, interviews, and standardized questionnaires

Method: 12 participants, all male from the department with overall programming experience ranged from 4 to 13 years; and their C# experience, between 1 and 8 years Participants were evaluated one by one Asked to modify a multimodal interaction that was described with both Hasselt and C# 10-minutes tutorial about Hasselt multi-modal prototype with which they had to interact according to the indications of the researcher Each participant had to sequentially perform the changes with both Hasselt and C#. The changes had to be performed within a time limit of 30 minutes per language Observations during the task, usability questionnaires(Single Ease Question (SEQ) questionnaire -¿ 7-point rating scale to assess how difficult users find a task, administered immediately after a user attempts a task in a usability test & System Usability Scale (SUS) 10 item questionnaire with

five response options for respondents; from Strongly agree to Strongly disagree) and immediately interviewed by the researcher. Results:

12 participants completed the experiment when using Hasselt; but only 10 succeeded with C# the others exceeded their allotted time. Completion time:

On average, changes made with Hasselt took 4.4 minutes in comparison with the 24.7 minutes when using C#.

Code testing effort On average, programmers tested their code 1.8 times when using Hasselt and 3.3 times when using C#. -? video recording the computer screen during the experiment is essential.

Aiding Programmers using Lightweight Integrated Code Visualization

Author[s]: Per Ola Kristensson, Chung Leung Lam Summary: This paper introduces a Lightweight Integrated Code Visualization (LICV) tool designed to aid programmers using Integrated Development Environments (IDEs), implemented as a plugin for Eclipse IDE for Java.

LICV continuously tracks the active editor in the IDE and visualizes up to 24 code features in a designated non-intrusiveview. LICV is designed to facilitate fast understanding of the structure of the code in order to help users carry out routine programming tasks.

The LICV tool is evaluated by carrying out 2 user studies that compared LICV against regular Eclipse in four tasks. LICV significantly reduced participants completion times by nearly 50

Problem Solved: Programming is a difficult error-prone process and as consequence tremendous research efforts have been devoted to aiding programmers. A third approach is to aid programmers via software visualization. However, most of these interfaces radically modify a part of the programmers existing user interface. we explore an alternative lightweight approach which does not radically change the user interface. Instead, it provides a complementary interactive visualization view that enables users to perceive structures in their active code editor at a glance.

three dependent variables: completion time (in seconds), number of errors, and users subjective pref- erence on an ordinal scale

Approach: To test this hypothesis we carried out an initial formative evaluation in order to determine if there is any merit to the LICV paradigm at all. One relatively inexpensive yet reasonably rigorous approach to assess the initial viability of LICV is controlled experiments, in particular, in the context of software engineering, controlled experiments have been criticised for being one-off results that are seldom replicated [15]. To increase the validity of our findings we therefore decided to carry out the same experimental design twice with two different sets of participants (and slightly different setups). As we we will see, the second replication experiment confirmed the results of the first experiment.

Method: 4 tasks Experiment 1: 9 computer science students via convenience sampling. The participants had on average four years of experience with Java (sd = 1.6) and three years of experience with the Eclipse IDE for Java (sd = 1.6). The least experienced participant had one year of experience and the most experienced participant had six years of experience with Java and Eclipse. Before testing participants were demonstrated how LICV works within Eclipse and offered a few minutes to familiarize themselves with the laptop and the Eclipse environment. In summary, the

two experiments are neither large enough, nor diverse enough in terms of the tasks they explore, to conclusively state whether LICV is successful in aiding programmers with routine tasks.

Evaluation 2: Replication with Remote Users

In the replication experiment we recruited seven participants via convenience sampling. The participants had on average five years of experience with Java (sd = 1.6) and three years of experience with the Eclipse IDE for Java (sd = 1.3). The least experienced participant had three years of experience with Java and one year of experience with Eclipse, while the most experienced participant had eight years of experience with Java and five years of experience with Eclipse.

The overall experimental procedure was identical to the first experiment. However, unlike the first experiment, in this experiment participants performed the experiment on their own laptops. They were instructed and supervised on the tasks via a videoconferencing facility.

GoHotDraw: Evaluating the Go Programming Language with Design Patterns (2010) Go, a new programming language backed by Google vs Java and C++

In this study, we evalu- ate Go by implementing design patterns Singleton, Adaptor, and Template Method, and porting the pattern- dense drawing framework HotDraw into Go, producing GoHotDraw. We show how Gos language features affect the implementation of Design Patterns, identify some potential Go programming patterns, and demonstrate how studying design patterns can contribute to the evaluation of a programming language.

Go is a language which aims to do things differently, adopting a new object model that is significantly different from most object- oriented languages. At least for classical object-oriented programs, such as drawing editors and frameworks, designs in Go do not seem to be significantly different to designs in Java or C++. In some circumstances, the differences between embedding and inheritance can make some patterns more difficult to implement, but Go-specific idioms (or patterns) can resolve most of these difficulties.

3 Research Activities

3.1 Mungo

Mungo[1] is a Java front-end tool, developed by Dr. Dimitrios Kouzapas at the University of Glasgow, used to statically check the order of method calls i.e. its typestate. It is implemented using the JastAdd framework[2][19]. A protocol or session type is represented as a separate typestate file, associated with a Java class. The protocol definition is described as a sequence of method calls, the order of which determines the validity of the protocol.

Mungo checks that the object instantiating the class performs method calls as defined by its typestate. If the protocol is not violated, standard .java files are produced for every .mungo file in the package. The resulting code can then be ran as any standard Java code.

[1] http://www.dcs.gla.ac.uk/research/mungo/

[2] http://jastadd.org/web/extendj/

Typestate is a refinement of the concept of a type in programming [7, 8]. Typestate is the constraining of a sequence of calls. In programming certain methods can sometimes only be called in certain states. Typestate checks what method is available to be called in which state and what the subsequence state of each method is. Furthermore Typestate can check at compile time that specifications are followed. Through Typestate analysis, it is possible to track the degree of initialisation of variables, guaranteeing that operations would never be applied on improperly initialised data.

The following work was undertaken on the Mungo tool:

- the tool has been moved from the Java 1.4 compiler to the Java 1.8 compiler and adapted to work with the new framework.(joint work with Dr. Dimitrios Kouzapas)
- moving the tool to a new compiler framework was a good opportunity for some refactoring(such as getting rid of dead code or method extraction).
- the tool has been extended to support Java enumerations.(joint work with Dr. Dimitrios Kouzapas)
- updated repositories
- work has been undertaken to support generic types
- work has been undertaken to typecheck exceptions, in a simple form at the moment

Areas of future work:

- aliasing
- typecheck generic types
- support annotations

3.2 StMungo

StMungo (Scribble to Mungo)[3] is a Java-based tool, developed by Dr. Ornela Dardha at the University of Glasgow, that translates a Scribble[30, 36] local protocol into a Mungo specification and skeleton socket-based implementation code. The resulting code is typechecked using Mungo. Scribble is a protocol description language that can describe how two or more participating entities interact should interact with each other.

After the Scribble protocol is translated to a Mungo specification, Mungo**??** is used to generate a Java implementation for the protocol. This tool allows an easy transition from a Scribble global protocol definition to working Java implementation. We start by specifying distributed multiparty protocol in Scribble. We can then use the Scribble toolchain to validate and project the global protocol into a local one describing the interactions from the point of view of a specific participant. For every Scribble local protocol, StMungo will produce .mungo files containing: a typestate specification describing the local protocol as a sequence of method calls, an API for the participant implementing the typestate methods and a main class skeleton calling the methods in the typestate.

[3] http://www.dcs.gla.ac.uk/research/mungo/

To improve this tool various extensions, refactoring has been undertaken:

- extended the tool to translate messages with no payload i.e.

```
message_operator ()
```

- extended the tool to translate messages with multiple payload i.e.

```
message_operator ( payload_type1 , ... , payload_typen )
```

- extended the tool to translate messages without a message signature i.e.

```
( payload_type1 , ... , payload_typen )
```

- extended the tool to translate messages with annotated payloads i.e.

```
message_operator ( annotation:payload_type)
```

- various small improvements to allow most translations to run without having to be edited by a human
- various improvements allowing the tool to crash gracefully
- adapted the tool to work with multiple versions of scribble specification
- improved the tool by implementing support for special cases of recursions nested in choice structures A simple example of a problematic scribble specification is:

```
global protocol Example(role S, role C) {
choice at C{
        rcpt(String) from C to S;
    } or {
        msg(String) from C to S;
        rec loop {
                subject(String) from C to S;
                continue loop;
            }
        }
    }
}
```

- improved the tool by implementing support for special cases of nested choice inside a recursion

  A simple example of a problematic scribble specification is:

```
global protocol ProtocolName(role S, role C) {
  command(String) from C to S;
  rec overall {
  choice at S
      {
      ok(String) from S to C;
                      choice at S {end(String) from S to C;}
                      or {
                      sum(String) from S to C;
                      }
                      message(String) from S to C;
      } or {    error(String) from S to C;      }
      continue overall;
  }
  }
```

- extending the tool to translate to support inlined protocols and sub-protocols(ongoing)
- kept it up to date with changes in Mungo
- refactoring(such as method extraction or getting rid of dead code) to keep everything simple
- regression testing to find any new bugs introduced

Areas of future work:

- test harness
- extension to translate more complex constructs such as interruptible or parallel
- keeping it up to date with changes in Scribble and Mungo
- formalise the translation and its semantics

3.3 Usecases

To better understand the expressive power of current session type technology together with any limitations that may need to be addressed, the current use case repository[4] was surveyed as a first step. As a second step, new real-world examples were sought. From the various protocols looked after, representations were attempted for two, Paxos and the File Transfer Protocol(FTP).

The first protocol chosen as a usecase was Paxos. Paxos is a protocol for solving consensus in a network of unreliable processes. It ensures that a single value among the proposed values can be chosen. It assumes an asynchronous, non-Byzantine model.[24]

Two major advantages of Paxos are that it is provably correct in asynchronous networks that eventually become synchronous and it does not block if a majority of participants are available. Furthermore it has provably minimal message delays in the best case. Despite it's reputation of being difficult to understand & implement it is widely, a couple of examples would be Google in Chubby[9], Yahoo use something based on it in ZooKeeper. The protocol comes with three roles and a two-phase approach. A proposer responsible for initiating the protocol, that handles client requests and proposes values to be chosen. An acceptor that responds to messages from proposers by either rejecting them or agreeing in principle and making a promise about the proposals it will accept in the future. An a listener or learner, who wants to know which value was chosen. Each Paxos server can act as any or all 3 roles.[25]

Some representations of the algorithm have been attempted using Scribble, combined with StMungo and Mungo to give a working Java code. However in trying to represent it some shortcomings of the toolset became apparent:

- representing broadcasting
- representing quorum/a majority

[4]https://github.com/epsrc-abcd/session-types-use-cases

- representing express the dynamic aspects such as processes failing, restarting
- express multiple instances of the protocol

The work on Paxos has been presented during the last ABCD meeting in January 2016. Work on a better Paxos representation has been paused for the moment, other tasks taking priority such as improving the tools.

The second protocol chosen was the File Transfer Protocol described by Request for Comments(RFC): 959[14]. FTP is a standard network protocol for transferring files between a client and server on a network. FTP is an unusual protocol in that it utilizes two ports, a data port and a command(control) port. FTP may run in active or passive mode, which determines how the data connection is established. In both cases, the client creates a TCP control connection from a random, usually an unprivileged, port number to the FTP server command port 21. Some representations of the algorithm have been attempted using Scribble, combined with StMungo and Mungo to give a working Java code. However in trying to represent it some shortcomings of StMungo became apparent. Hence, work on an FTP representation has been paused to improve StMungo and Mungo, to allow a better representation.

Work on both usecases is planned to be restarted in the autumn, and make the base for a paper later on in the year.

3.4 User study

New programming language constructs are more often than not introduced without first exploring how well suited their are for their purpose or how they would be used in the real world. While proving they solve the problem is a good thing, checking how well they solve it would be nice. To explore how well programmers would interact with session types an initial study has been devised. This can be found in appendix **??**. It is intended to explore whether programmers can learn what session types are, identify how they should be used, and reason about session typed code correctly. At this stage there are little constraints on the type of participant. Since one of the claims behind session types is that they make reasoning about communication easier, participants with less programming experience are welcome. It would be interesting to see if there are any differences and what differences there are between participants of different backgrounds. The only requirement in this case being a working knowledge of Java.

Difficulties: choosing meaningful for the user to carry out, deciding what constitutes a good understanding of session types.

4 Other Activities

As part of the first year of my PhD, various additional activities have been undertaken, such as training courses(detailed in appendix**??**), ABCD group meetings of various sizes, seminars and talks(e.g. Tht Scottish programming language seminar series, FATA seminars) which improved my knowledge of the field and gave me some insight of the exciting research ongoing, as well as my own ignorance. Some notable events attended were the BETTY (Behavioural Types for Reliable

Large-Scale Software Systems)[5] meeting in March, and Wadlerfest[6], held in celebration of Philip Wadler's 60th birthday, or LFCS30[7], to celebrate the 30th anniversary of the founding of the LFCS.

5 Future Work

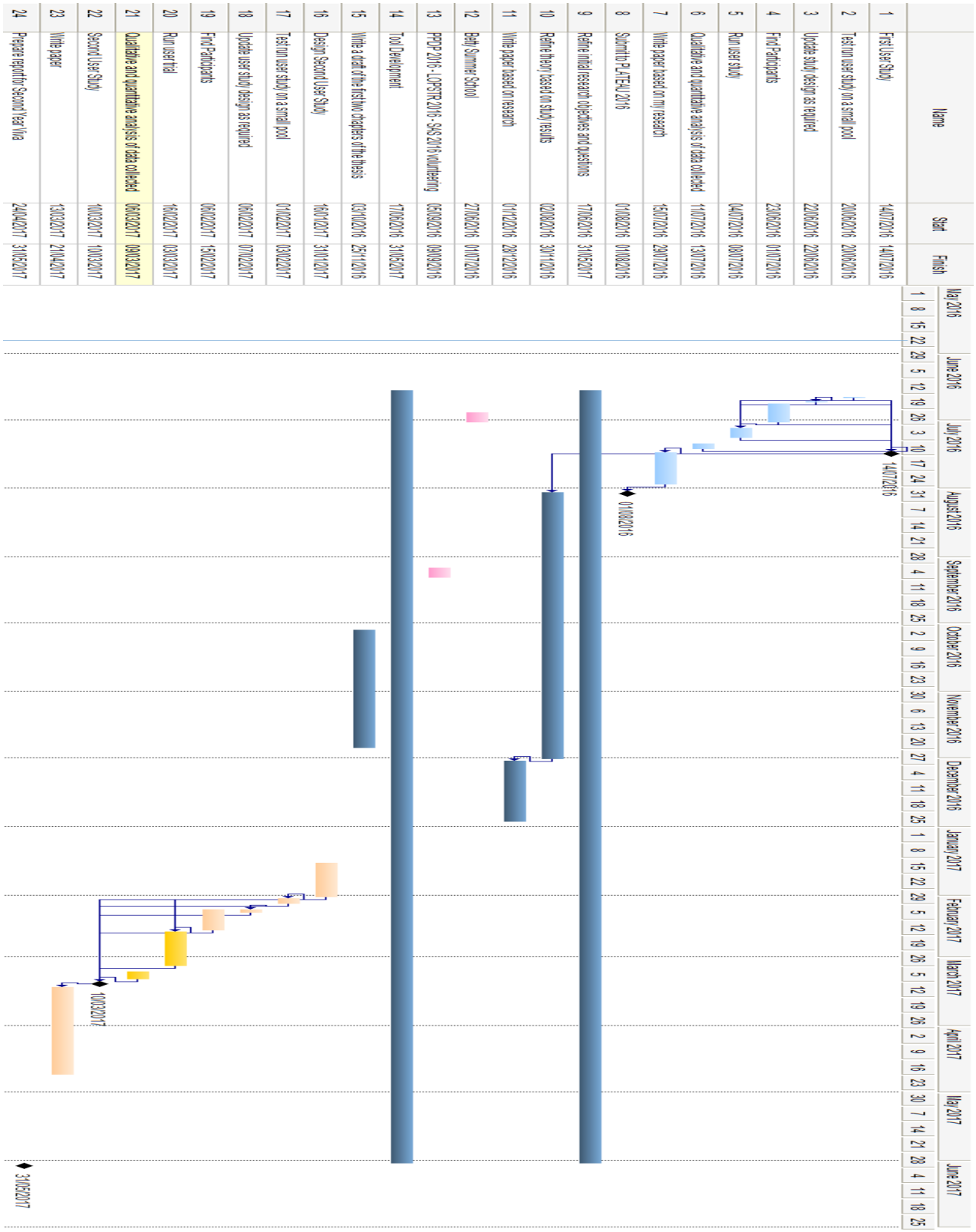
Some of the future work planned has been highlighted throughout this report. The activities planed for next year fall into several interconnected themes:

- Language usability and evaluation. As mentioned above in 3.4 a user study is in plan for the near future, its results to be analysed and written up and submitted to PLATEAU 2016[8]. A second more focused study is also in plan for the later part of the year.
- Tool development. Some of the work that is to be done has already been discussed earlier, however it is expected that the need for various different improvements will arise. Thus this will be an ongoing activity through the year.
- Training and development. This category contains any training courses required by the school as well as any academic events to be attended. Over the summer, I will attend BETTY (Behavioural Types for Reliable Large-Scale Software Systems) in Limassol, Cyprus. The summer school will cover closely related areas of interest such as multiparty session types, linear logic, Practical programming with session types. In September I will help with the PPDP, LOPSTR and SAS conferences in Edinburgh.
- Refining initial research objectives and questions. This is really the miscellaneous category, containing work to be continued such as the usecases**??**, and any new ideas that will arise from the user study.

For a detailed plan, a Ganntt chart is available in appendix A.

[5] http://www.behavioural-types.eu/meetings/wg-mc-meetings-17th-18th-march-2016-in-malta
[6] http://events.inf.ed.ac.uk/wf2016/
[7] http://events.inf.ed.ac.uk/lfcs30/
[8] http://2016.splashcon.org/track/plateau2016

A Second Year Plan



B User Study Plan

1 Experimental Description

The next part of this document is concerned with what will be evaluated and how. The following sections will define the methodology and approach that will be taken.

1.1 Tasks to complete

The participants will be given three main tasks to complete with various subtasks.

1. Iterator example in Mungo. Code provided. Spot and correct the error. Add the remove operation.
2. SMTP[1] example in Scribble and Mungo. Code provided. StMungo introduced as well. Spot and correct the error one in scribble specification, second one in Mungo specification.
3. Implement a small example based on an informal specification. Buyer seller would be a good candidate here.

1.2 Variable/Experimental conditions

Independent variables:

- Programming expertise

Dependent variables to be measured:

- time to complete each task
- how many times the code is compiled
- how many bugs/errors
- is the end result correct

1.3 Data Collection/Measurements/Observations

The purpose of this study is exploratory. Dependent variables to be measured:

- time to complete each task
- how many times the code is compiled
- how many bugs/errors are encountered in the process
- is the end result correct
- participants' opinion about the tools/session types

1.4 Design

Considering that the aim of this experiment is exploratory and the learning effect (performance improving with experience, even over very short periods of time) is of little concern in this case a within subjects design, every participant perform every task under every condition, will be used.

[1] http://www.ietf.org/rfc/rfc2821.txt

1.5 Participants/Subjects/Users (Controlled Variable)

The only requirement for participants is that they have some Java experience. Factors like level of programming proficiency, background, or upfront knowledge of behavioural types or session types will be taken into consideration.

1.6 Experimental location

The experiment will be carried out in Sir Alwyn Williams building, room F112. This office has been chosen as it allows a higher degree of control over the environment, the programming one in particular.

1.7 Experimental schedule

This section outlines all of the parts of the experiment and a rough estimate how long each will take. After completing all tasks, anticipated to take roughly 45 minutes, the participants will be asked to answer a short survey rating their experience using session types. The time taken to complete the experiment may be longer or shorter depending on the level of programming expertise.

1. 5 minutes to explain the experiment
2. 15 minute practical tutorial on session types, typestate, the tools to be used
3. approximately 10 minutes for task 1
4. approximately 15 minutes for task 2
5. approximately 20 minutes for task 3
6. 5 minute short informal interview
7. 5 minute to complete survey
8. 5 minutes for any questions the participant might have

C Training Needs Analysis Form

University of Glasgow | College of Science & Engineering

Training Needs Assessment and Record 2015

Name	Adriana Laura Voinea	Year of Study	First	School	Computing Science		
Date Discussed with supervisor	03/06/2016	Date Submitted	16/06/2016	Funding Source	EPSRC	Total Credits	11

The areas below correspond to those detailed in the Researcher Development Framework . You should select the areas you would like to develop and discuss these with your supervisors. You may be able to obtain the skills you require through training and/or practical experience. The completed TNA/Record should be submitted to the Graduate School when you submit your paperwork for your annual progress review.

DOMAIN A – KNOWLEDGE AND INTELLECTUAL ABILITIES				
	Development Required	Courses identified from the Doctoral Research training programme and elsewhere and any practical experiences you intend to undertake to develop the skills required	Courses attended and dates	Credits
A1 – Knowledge Base Includes subject knowledge, research methods, information search skills and management, languages	Knowledge of Statistics	RSDA 6107 Introduction to Statistical Inference	Attended on 27/05/16	1
		RSDA 6108 Introduction to Statistical Modelling	Attended on 28/05/16	1
		RSDA 6109 Introduction to Design and Analysis of Experiments	Attended on 29/05/16	1
	Programming language theory	Scottish programming language seminars	Attended on various dates throughout the year	N/A
		Betty meeting	Attended on 17-18 March 2016	N/A
A2 – Cognitive abilities	Literature review	RSDA 6083 Literature critique/ review SC	Not attended as it was cancelled due to illness	N/A

Includes analysing, synthesising, critical thinking, evaluation and problem-solving skills				
A3 – Creativity Includes developing inquiry skills, intellectual insight, innovation, constructing an argument, intellectual risk	Inquiry skills, constructing an argument	Project meetings Scottish programming language seminars FATA seminars	Attended on various dates throughout the year Attended on various dates throughout the year Attended on various dates throughout the year	N/A N/A 1

DOMAIN B – PERSONAL EFFECTIVENESS				
	Development Required	Selected Courses from the Doctoral Researcher Development Training Programme	Date Course(s) Attended	Credits
B1 – Personal qualities Includes enthusiasm, perseverance, integrity, self-confidence, responsibility	Self-confidence, responsibility	Mini Project	10/15-01/16	N/A
B2 – Self management Includes preparation and prioritisation, commitment, time-management, work-life balance, responsiveness to change	Prioritisation, time-management, project management	RSDC 6001 Project management – An Introduction	Attended on 01/03/2016	1
B3 – Professional and career development Includes career management, continuing professional development,	Networking, continuing professional development	Attended Seminars (SPLS) Attended Betty Meeting WadlerFest/LFCS30	Attended on various dates throughout the year Attended on 17-18 March 2016 Attended on 11-13 April 2016	N/A N/A 1

responsiveness to opportunities, networking				

DOMAIN C – RESEARCH GOVERNANCE AND ORGANISATION				
	Development Required	Selected Courses from the Doctoral Researcher Development Training Programme	Date Course(s) Attended	Credits
C1 – Professional conduct Includes health and Safety, ethics, principles and sustainability, IPR/copyright, respect and confidentiality, attribution and co-authorship, appropriate practice	Improve knowledge of IPR/copyright, respect and confidentiality, attribution and co-authorship	RSDC 6023 Research Integrity Equality and Diversity Online Training	Attended on 21/01/2016 Completed on 25/05/2016	1 1
C2 – Research management Research strategy Project planning and delivery Risk management	Improve knowledge of data management	RSDC 6025: Research Data Management	Attended on 17/02/2016	1
C3 – Finance, funding and resources Includes incomes and funding generation, financial management, infrastructure and resources	Funding generation, financial management, infrastructure and resources	FATA seminars	Throughout the year	N/A

DOMAIN D – ENGAGEMENT, INFLUENCE AND IMPACT				
	Development Required	Selected Courses from the Doctoral Researcher Development Training Programme	Date Course(s) Attended	Credits
D1 – Working with others	Collaboration skills	Attended Project Meetings	Multiple dates: September 2015 – now	N/A

Includes collegiality, team-working, people management, supervision, mentoring, influence, leadership, collaboration, equality and diversity				
D2 – Communication and dissemination Includes communication methods, communication media, publication	Improve presentation skills	RSDD6002: Presenting with Impact	Attended on 12/05/2016	1
D3 – Engagement and impact Includes teaching, public engagement, enterprise, policy, society and culture and global citizenship	Teaching Teaching training	Tutored 2nd Year Course: JOOSE2 Tutored 2nd Year Course: WAD2 Graduate Teaching Assistant Statutory Training	10/2015 – 03/2016 01/2016 – 03/2016 Attended on 26/20/2015	N/A 1

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